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ORIGINAL

EVALUATION OF THE HYDROGEOLOGIC SYSTEM AND CONTAMINATION MIGRATION PATTERNS ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

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13. ABSTRACT (Maximum 200 words)

THE PRIME OBJECTIVE OF THIS STUDY WAS TO CHARACTERIZE THE HYDROGEOLOGIC CONDITIONS AND CONTAMINATION MIGRATION PATTERNS AT RMA. THE ENTIRE STUDY WAS DIVIDED INTO FOUR PHASES. PHASE I WAS TO CHARACTERIZE THE HYDROGEOLOGICAL CONDITIONS AND CONTAMINATION MIGRATION CONDITIONS AT THE ARSENAL. PHASE II WAS TO EVALUATE AND INTERPRET THE HYDROGEOLOGIC SYSTEM, GROUND WATER FLOW AND CONTAMINATION MIGRATION PATTERNS. PHASE III INCLUDED ESTIMATING GROUND WATER IMPACTS CAUSED BY THE CONSTRUCTION OF A CONTAINMENT BARRIER AROUND BASIN F. PHASE IV INCLUDED THE PREPARATION OF A REPORT DESCRIBING ALL THE WORK, RESULTS, CONCLUSIONS AND RECOMMENDATIONS.

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EXECUTIVE SUMMARY

During the past several years, geotechnical studies have been conducted at Rocky Mountain Arsenal. These included separate studies at the North Boundary area, Basin A area, Basin F to the North Boundary, Basins B, C, D, and E, Basin A Neck areas, Basin F area, and the Northwest Boundary area.

These projects both individually and collectively, have contributed valuable information concerning the hydrogeology and contamination patterns at Rocky Mountain Arsenal. However, each of these projects was undertaken in a geographically defined area, and the information was not integrated on an Arsenal-wide basis.

An overall data assessment was prepared by Geraghty & Miller, Inc. to provide an integrated evaluation of hydrogeological data for the purpose of analyzing ground-water flow and contaminant migration.

Regionally, ground-water flow under the Arsenal is one continuous system from southeast to northwest toward the South Platte River Valley. Flow occurs in both the alluvium and bedrock aquifer units.

Contours on the water table verify the existence of an anomalous 30-foot high mound below the South Plants. This mound created by leakage of cooling water into low-permeability material, acts as a major driving force to the ground-water system.

Vertical flow of ground water has been identified in the South Plants and Basin A Neck areas and water from the alluvium has the potential to migrate into deeper formations.

A flow-net analysis and quantification of ground-water flow could not be made because of complicated hydrogeology, lack of sufficient regional control data, lack of contaminant stratification information, and contradictory field permeability values.

Primary sources of ground-water contamination are the South Plants area and Basin A. Secondary sources are Basin F and the sanitary and industrial waste sewer lines.

Four chemical constituents in ground water, chloride, DIMP, DCPD, and DBCP (Nemagon) were mapped to determine their lateral and vertical distribution. All plumes extend across the north boundary of RMA in reduced concentration. Similarly, chloride and DIMP plumes extend across the northwest boundary.

The chloride plume is largest with major concentrations (5,000 mg/l) near Basins A and F. The DIMP plume has concentrations of 10,000 to 20,000 ug/l near Basins A, C, and F. DCPD plumes originate at the South Plants, Basins A and F with concentrations of 2,000 to 15,000 ug/l. Major Nemagon concentrations occur at the South Plants (30,000 ug/l) and plumes are present below Basins C and F.

Vertical migration of chloride, DIMP, DCPD, and Nemagon has occurred in the Basin A Neck and South Plants areas.

Vertical migration of contaminated water through abandoned farm wells on the Arsenal is possible. Eight such wells tapping deeper aquifers are located within the plumes.

The configuration and movement of contaminant plumes is in accordance with the ground-water flow pattern. Contaminated ground water from the southern portion of the Arsenal continues to move to the north and northwest boundaries.

Four Basin F containment schemes were simulated by means of a digital computer model to determine their impact on ground-water flow. Schemes studied were combinations of a bentonite clay barrier around Basin F, dewatering wells and injection wells. Changes in ground-water flow across the north and northwest RMA boundaries were computed. Placement of a bentonite barrier around Basin F may produce a small amount of upward leakage of artesian water.

Data gaps exist because of uneven distribution of wells and paucity of subsurface information along the northwest boundary, South Plants, the southern and eastern portion of the Arsenal, and the Basin A Neck area. Work plans to fill some of the data gaps have been prepared and a 69-well regional drilling program has been initiated.

In spite of the great volume of data presently available, no conclusions can be made regarding site-specific problems such as Basin F leakage, the role of the sewer lines, and the situation at the south lakes, First Creek and irrigation laterals. Limited test drilling along the northeast side of Basin F is recommended.

Reduction and integration of the present ground-water monitoring program is recommended in order to arrive at a more manageable cost-effective system. Arsenal-wide program objectives should be incorporated.

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FIGURES (Cont'd.)

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PLATES (Cont'd.)

EVALUATION OF THE HYDROGEOLOGIC SYSTEM AND CONTAMINATION MIGRATION PATTERNS ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

1.0 INTRODUCTION

1.1 Objectives

Geraghty & Miller, Inc. was retained in December 1979 by the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA), Aberdeen Proving Ground, Maryland, through the AAI Corporation of Baltimore, Maryland. The prime objective of this study was to characterize the hydrogeologic conditions and contamination migration patterns at Rocky Mountain Arsenal, Denver, Colorado.

The entire study was divided into four phases. Phase I was to characterize the hydrogeological conditions and contamination migration conditions at the Arsenal. Phase II was to evaluate and interpret the hydrogeologic system, ground-water flow and contamination migration patterns at Rocky Mountain Arsenal (RMA). Phase III included estimating ground-water impacts caused by the construction of a containment barrier around Basin F. The final phase, Phase IV, included the preparation of a report describing all the work, results, conclusions, and recommendations.

During this study the hydrogeologic system and the ground-water flow system, including the geometry of the flow system, directions of flow (horizontal and vertical), and the hydraulic forces driving the system, were determined. The analysis of the hydrogeologic conditions included determining the interrelationships of the different aquifers, and the interconnection of aquifers and confining layers. The contamination migration patterns were analyzed by using four constituents: chloride, diisopropylmethylphosphonate (DIMP), dicyclopentadiene (DCPD), and 1,2-dibromo, 3-chloropropane (DBCP, known by its trade name Nemagon). These constituents were selected for the following reasons: the State of Colorado has issued a cease-and-desist order relating to the movement of DIMP and DCPD across the RMA boundary. In addition, DIMP is a highly mobile constituent while DCPD is relatively immobile, allowing comparisons to be made of differential migration. Nemagon (DBCP) was selected because of its reported high toxicity. Chloride, a conservative constituent and an excellent tracer, was selected because it has been mapped in previous years thus allowing comparisons to be made. The report presents the possible sources of contamination and describes potential contaminant migration.

During this study the hydrogeologic description of the Arsenal was integrated into a regional perspective. A vertical description of hydrogeology and contamination migration, as well as the Arsenal-wide picture were combined. In analyzing and interpreting the data, many gaps and problems were found which are enumerated in this report. Recommendations and work plans to collect the additional information necessary to fill major data gaps are summarized.

1.2 Acknowledgements

The authors wish to express their appreciation to Mr. Donald L. Campbell and Mr. Joseph H. Zarzycki of USATHAMA for assistance with the organizational and technical portions of this program, and aid in communications between the Arsenal staff and consultants.

The authors also acknowledge the cooperation and assistance provided throughout the project by Mr. F. James Schroeder of the AAI Corporation of Baltimore, Maryland, and personnel at Rocky Mountain Arsenal. Dr. William McNeill aided in organizing a cooperative effort between the various groups at Rocky Mountain Arsenal and Geraghty & Miller, Inc. The authors also thank Mr. Brian L. Anderson, whose intimate knowledge of the hydrogeology of Rocky Mountain Arsenal greatly aided our study, and Dr. James Krell of MISO for helping us to obtain information from the computer.

1.3 Sources of Information and Data

Geraghty & Miller, Inc. reviewed more than 50 reports and maps prepared by USATHAMA and RMA personnel or government consultants. Reports and data were also collected from the U.S. Geological Survey (USGS) and the State of Colorado Department of Natural Resources. Much of the raw data were obtained from MISO and local RMA access to the IR Data Management System. The data from the computer included not only raw data but also hydrogeologic descriptions and lines of section. Geologic, hydrogeologic, and chemical data from more than 100 deep wells (over 75 feet) and 200 shallow wells were analyzed to construct the cross sections. For the contamination migration and water-table maps, data from more than 350 wells were analyzed. For information related to off-post analyses, USGS files were searched for hydrogeologic, ground-water flow, and contamination data. The regional geology was obtained from studies carried out by both the USGS and the Department of Natural Resources of the State of Colorado.

2.0 REGIONAL HYDROGEOLOGY

2.1 Description of Aquifers

The RMA is located in the northwestern portion of the Denver Basin, a geologic structural depression of some 6,000 square miles. This oval basin, measuring roughtly 120 by 70 miles, is filled with about 15,000 feet of sedimentary rocks composed mostly of sandstones, shales, and conglomerates. Carbonate rocks are restricted to occasional thin discontinuous beds. The sedimentary rocks are overlain by a thin cover of alluvial deposits. The stratigraphic sequence of the various formations in the Denver Basin is shown in Figure 1.

Ground water is obtained from alluvial deposits in the South Platte River valley and from several bedrock aquifers. Major bedrock aquifers are, from oldest to youngest, the Fountain and Lyons Formations, the upper and lower parts of the Dakota Group, the Laramie-Fox Hills aquifer (the combined thickness of the Milliken sandstone member of the Fox Hills Formation and the A and B sandstones of the Laramie Formation), the upper part of the Laramie Formation, and Arapahoe, Denver and Dawson Formations. Cross sections illustrating geologic conditions in the Denver Basin are shown in Figure 2.

The Fountain and Lyons and Dakota Group aquifers are only tapped by a small number of wells in their outcrop areas along the margin of the basin; elsewhere these aquifers lie at too great a depth. Wells completed in these aquifers repcrtedly yield only small quantities of water (5 to 50

Era	System or Period	Series	Geologic Unit	
Cenozoic	Quaternary	Recent and Pleistocene	Quaternary surficial deposits	Stream channel, flood-plain and terrace deposits; eolian sand, etc.
	Tertiary	Oligocene	Castle Rock Conglomerate	
			Tertiary intrusive and extrusive rocks	
Cenozoic and Mesozoic	Tertiary and Cretaceous	Paleocene ---?--- Upper Cretaceous	Dawson Group	Dawson Arkose
				Denver Formation
				Arapahoe Formation
Mesozoic	Cretaceous		Laramie Formation	Upper part
				B sandstone
				A sandstone
			Fox Hills Sandstone	Milliken Sandstone
				lower part
			Pierre Formation	
			Niobrara Formation	Smoky Hill Shale
				Fort Hayes Limestone
			Benton Formation	Carlile Shale
				Greenhorn Limestone
				Graneros Shale
		Lower Cretaceous	Dakota Group	South Platte Formation
				Lytle Formation
	Jurassic	Upper Jurassic	Morrison Formation	
			Ralston Creek Formation	
Paleozoic	Triassic ? and Permian		Lykins Formation	Strain Shale
				Glennon Limestone
				Bergan Shale
				Falcon Limestone
				Harriman Shale
	Permian		Lyons Sandstone	
	Pennsylvanian		Fountain Formation	
			Glen Eyrie Formation	
	Mississippian		Madison Limestone	
			Williams Canyon Limestone	
	Ordovician and Cambrian		Manitou Dolomite	
	Cambrian		Sawatch Sandstone	
Precambrian			crystalline rocks	

| Principal Aquifers

(Romero, 1976)

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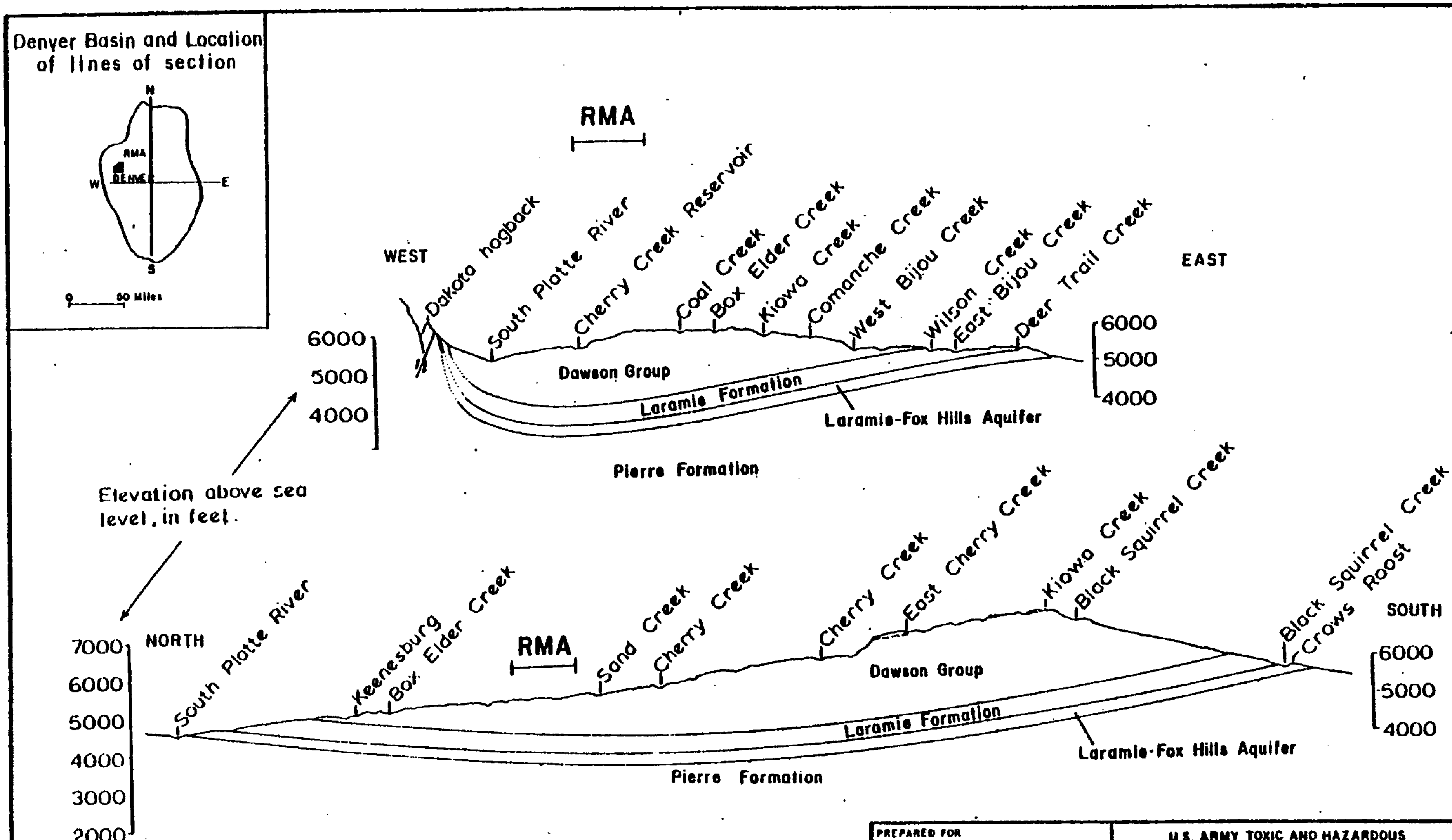
GENERALIZED STRATIGRAPHIC SECTION OF THE DENVER BASIN, COLORADO

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY F. von der Leeden PREPARED BY A. Leal PROJECT MANAGER R. Stollar	DATE JUNE 1980 SCALE	FIGURE 1



(Modified from Romare, 1976)

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CROSS SECTIONS OF THE DENVER BASIN

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY F. van der Leeden PREPARED BY A. Leal PROJECT MANAGER R. Stollar	DATE JI" " 1980 SC	FIGURE 2

gpm (gallons per minute)).

The Laramie-Fox Hills aquifer is the deepest major aquifer in the Denver Basin. The water-bearing sandstones that constitute this aquifer have a combined thickness of 200 to 400 feet. In the Denver metropolitan area, the depth to the aquifer is 1,200 to 1,500 feet. About 600 wells tap the Laramie-Fox Hills and yields of individual wells are 100 gpm and higher. Of these wells, over 80 percent are used for domestic and stock supplies. About 46 municipal wells obtain water from this aquifer in the Denver Basin. Total pumpage from the Laramie-Fox Hills aquifer is about 20 mgd (million gallons per day). The quality of water from this aquifer is good but there are local quality problems due to excessive concentrations of naturally occurring hydrogen sulfide, methane, iron, fluoride, and sodium.

The upper Laramie sandstones lie about 100 to 200 feet above the Laramie-Fox Hills aquifer. These sandstones, each about 10 to 20 feet thick, are relatively undeveloped aquifers that are capable of supplying small quantities (5 to 20 gpm) of water to wells.

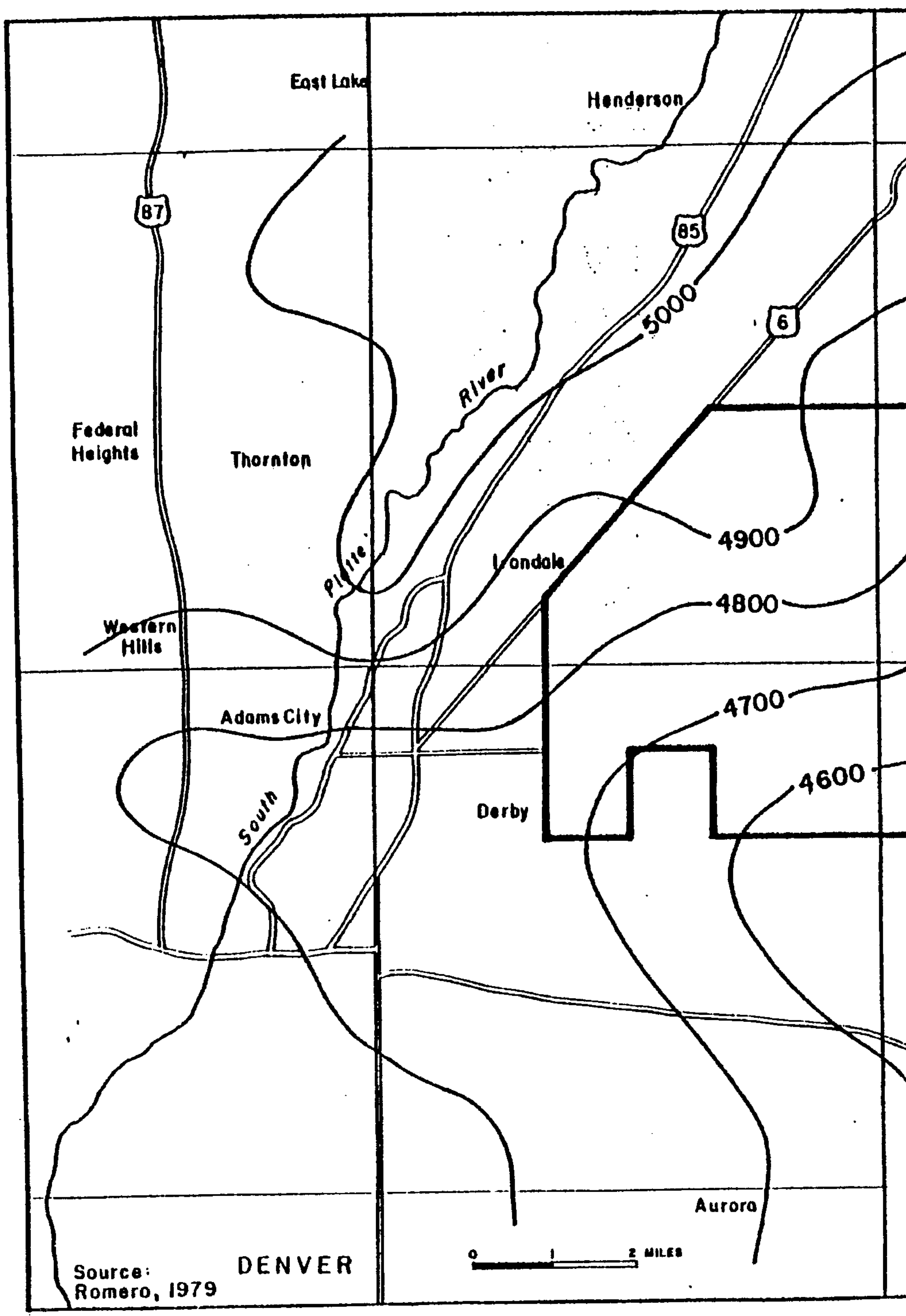
Above the Laramie Formation are a series of sandstones (Dawson Group) each of which is considered a separate aquifer. The basal aquifer of the group is the Arapahoe Formation with a thickness of 500 to 600 feet. This aquifer has proven to be a reliable source of good to excellent quality water and is tapped by about 6,000 wells. Well yields range from 100 to 500 gpm. Of these wells, 90 percent are used for stock and domestic use. The aquifer is used by some 130 municipal wells, including those of the Cities of Westminster and Arvada. A structure contour map of the top of the Arapahoe Formation in the Denver area is shown in Figure 3. At the RMA, depth to the Arapahoe decreases from about 700 feet below land surface along the southern boundary to about 300 feet along the northwest boundary.

Overlying the Arapahoe Formation are claystones, shales, sandstones, and conglomerates of the Denver Formation. The sandstone beds in the Denver Formation are irregular and discontinuous and commonly grade into clays and shales. A few beds of lignitic coal are present locally. These Denver bedrock units crop out at the RMA.

The Dawson Arkose consists of sandstone, conglomerate, and shale and has proven to be a reliable source of good quality ground water in the Denver Basin. Information regarding the presence or absence of this unit below the RMA is non-existant.

2.2 Ground-Water System

Pumping test data indicate that the transmissivity of the Denver and Arapahoe aquifers ranges from 80 to 3,600 gpd/ft (gallons per day per foot). High values occur where the wells penetrate thick sections of sandstone. A tentative estimate of natural recharge (including vertical leakage) to the Arapahoe-Denver sequence in the entire Denver Basin is about 100 mgd. As estimated pumpage from these aquifers is close to 150 mgd, it is clear that an imbalance exists. Ground water has been taken from storage within the aquifers resulting in a water-level decline of 100 to 200 feet in the Denver metropolitan area. These water-level declines in the bedrock aquifers are causing considerable concern to the state's water administrators.



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CONTOURS ON TOP OF ARAPAHOE FORMATION

(IN FEET ABOVE MEAN SEA LEVEL)

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY F. van der Leeden PREPARED BY A. Leal PROJECT MANAGER R. Stollar	DATE JUNE 1980 SCALE SHOWN	FIGURE 3

The alluvial deposits reach a maximum thickness of 130 feet and yield large quantities of water where saturated. Municipal water wells tapping the alluvial aquifer in Cherry Creek valley, for example, yield 900 to 1,800 gpm. Hundreds of irrigation and domestic wells tap the alluvial aquifer in the South Platte River valley. The volume of ground water moving through the alluvial aquifer is considerable. The USGS estimates that underflow in the South Platte River alluvium north of the Denver City line is about 10 mgd.

In the metropolitan area, ground water in the alluvium is rather mineralized and of poor quality, with an average total dissolved solids (TDS) concentration of 1,300 mg/l (milligrams per litre). The water is unsuitable for domestic and municipal supplies but is utilized where better quality water is not available.

Recharge to the water-bearing formations in the Denver basin is from both natural and artificial sources. Natural recharge is from precipitation (11 to 17 inches per year) on the outcrop area, infiltration of surface water in fault zones and stream valleys, and vertical leakage from confining beds. Artificial recharge is from leaking water-storage reservoirs and infiltration of sewage effluent, irrigation and industrial water.

Studies carried out by the Colorado Division of Water Resources and the USGS show that all bedrock aquifes are artesian; that is, in all wells, the water level rises above the bottom of the upper confining bed. This level to which the water rises is called the potentiometric surface. Ground-water discharge is occurring near some outcrops in areas where the potentiometric surface is above the land surface. Seeps and springs are present along a 70-mile length of Laramie-Fox Hills outcrop/subcrop that begins 12 miles east of Byers and runs north to an area 12 miles southeast of Greeley. There is some evidence that members of the Dawson Group might be discharging water at the land surface; however, potentiometric data are too limited to confirm this so specific discharge areas cannot be identified.

Regional ground-water flow in the bedrock aquifers is generally from south to north. The natural ground-water flow pattern in the principal aquifers has been modified considerably as a result of artificial discharge from numerous wells. As was pointed out previously, pumping of large quantities of water has led to considerable potentiometric decline in the major aquifers. In the metropolitan area, both the Laramie-Fox Hills and the Dawson Group (Arapahoe and Denver Formations) have experienced declines in head ranging from 100 to 600 feet. However, according to Romero (1976), the aquifers have not lost their capacity to deliver large quantities of water to wells, and some additional water-level decline can be tolerated.

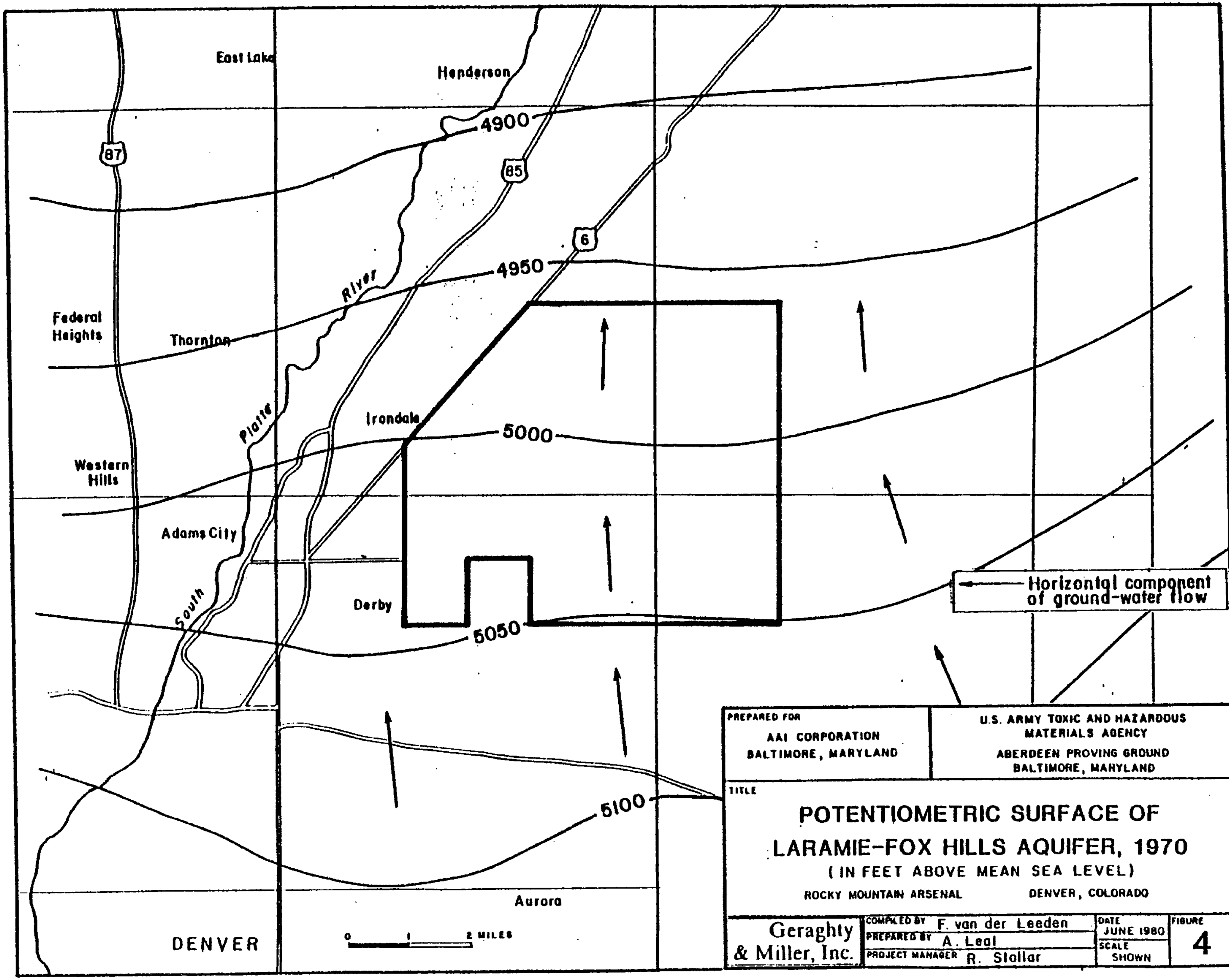
Two regional cross sections were constructed to illustrate hydrogeologic conditions below the RMA to a depth of 2,000 feet below land surface (Plate 1). The aquifers above the Pierre Shale are mapped based on well logs presented in Basic Data Report No. 15 (McConaghy and others, 1964), which includes the deep abandoned injection well at the RMA. As shown in the illustration, the formations rise in elevation north and west of the Arsenal in accordance with the regional geologic structure.

Figure 4 shows the potentiometric surface of the Laramie-Fox Hills aquifer as presented by Romero (1974). As shown, heads decline to the north at a rate of 20 feet per mile so that ground-water flow would be northward. The elevation of the potentiometric surface below the RMA is about 5,000 feet.

Figure 5 shows the potentiometric surface of the Arapahoe aquifer as of 1978 based on data obtained from the USGS (Robson, 1980). The basin-wide ground-water flow in the Arapahoe is north/northwest, but there are several cones of depression south of the arsenal which affect the flow system. Below the arsenal, the potentiometric surface of the Arapahoe in 1978 appeared to be at an elevation of 5,000 to 5,100 feet, but heads were 100 feet lower in the Aurora-Denver area, reflecting local pumpage. It should be noted that no Arapahoe observation wells exist at the RMA, and the potentiometric map was prepared from a limited number of control wells. However, it seems likely that water in the Arapahoe moves west below the RMA and then north or south in response to hydraulic gradients.

Comparing Figures 4 and 5 it can be seen that, below the RMA, the 1978 potentiometric surface of the Arapahoe was at the same elevation or only slightly above that of the Laramie-Fox Hills in 1974. More recent Laramie-Fox Hills and Arapahoe water-level readings are not available to evaluate present-day head relationships below the RMA.

The water table in the RMA region was first mapped in April 1956 (Petri and Smith, 1956). Their contour map showing the water-table configuration from the south RMA boundary to the South Platte River is shown in



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POTENTIOMETRIC SURFACE OF LARAMIE-FOX HILLS AQUIFER, 1970

(IN FEET ABOVE MEAN SEA LEVEL)

ROCKY MOUNTAIN ARSENAL — DENVER, COLORADO

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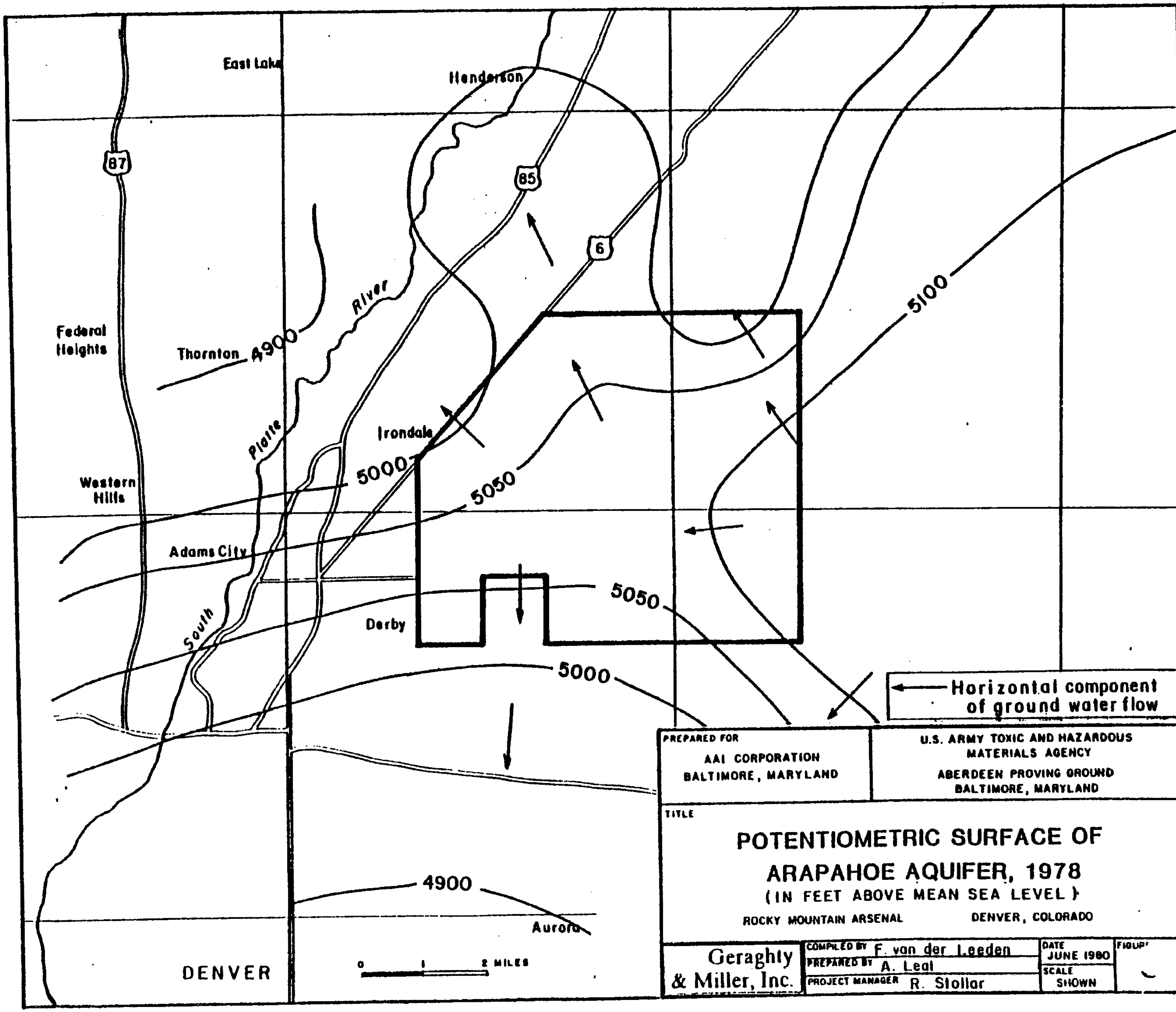

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POTENTIOMETRIC SURFACE OF ARAPAHOE AQUIFER, 1978

(IN FEET ABOVE MEAN SEA LEVEL)

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

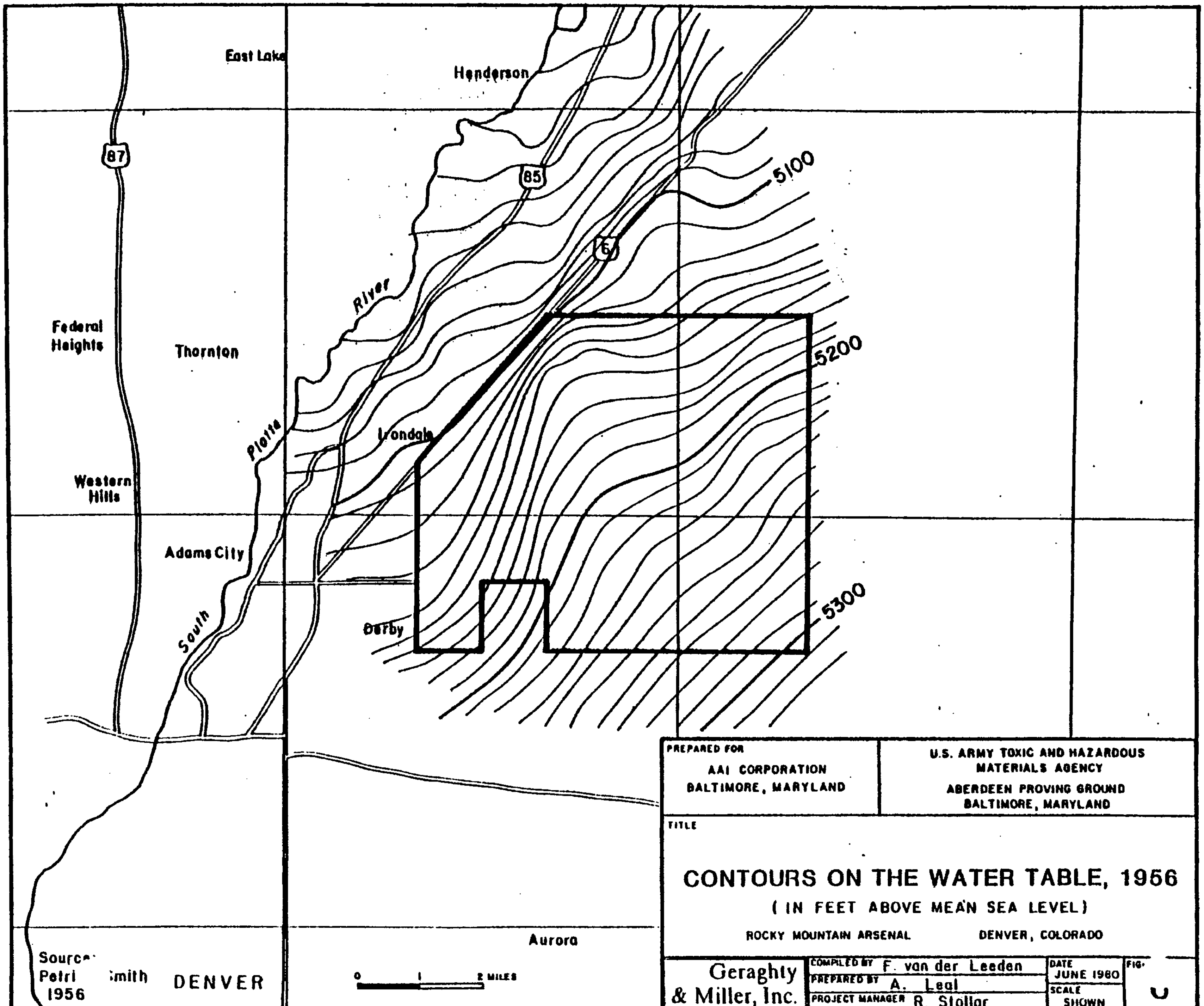
Geraghty & Miller, Inc.	COMPILED BY F. van der Leeden	DATE JUNE 1980	FIGURE
	PREPARED BY A. Leal	SCALE SHOWN	
	PROJECT MANAGER R. Stollar		

Figure 6. Water-table elevations ranged from a high of 5,300 feet in the southeast corner of the RMA to 5,100 feet along the northern boundary. Regional ground-water flow was to the northwest across the RMA toward the South Platte River. A detailed water-table contour map based on hundreds of water-level measurements made in RMA wells in 1979 described in Section 3.3 shows that, in spite of local anomalies, the regional flow patterns mapped in 1956 is unchanged and prevails today.

2.3 Ground-Water Quality

The quality of ground water in the alluvial and bedrock aquifers of the Denver Basin varies considerably. Table 1 presents selected chemical analyses of ground water from wells tapping the alluvium, the Dawson Group (which includes the Denver and Arapahoe Formations), the Laramie Formation, the Laramie-Fox Hills sandstone and the Precambrian crystalline rocks.

The quality of water in the alluvial aquifers is controlled by the source of recharge. The average TDS concentration of ground water in alluvium of the South Platte River near Denver is about 1,300 mg/l and increases downstream to about 1,800 mg/l at the Colorado state line. This water is not used for domestic and municipal supplies except where better quality water is not available. Although it is used for irrigation, some of the water is of salinity-hazard classification. The actual chemical composition of water in the valley-fill aquifers varies greatly, even within local areas. Generally, the total hardness exceeds 200 mg/l, and concentrations of TDS and sulfate exceed the U.S. Public Health Service recommended limits for drinking water (500 and 250 mg/l, respectively).



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CONTOURS ON THE WATER TABLE, 1956

(IN FEET ABOVE MEAN SEA LEVEL)

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.

COMPILED BY F. van der Leeden	DATE JUNE 1980	FIG.	U
PREPARED BY A. Leal	SCALE SHOWN		
PROJECT MANAGER R. Stollar			

Table 1. Tabulation of Selected Chemical Analyses of Ground Water in the Denver Basin, Colorado. (Concentrations in mg/l, except pH.)

Aquifer	Number	Range	Mean
Dissolved Solids (residue on evaporation at 180°C)			
Alluvium	106	141 - 2,870	880
Dawson Arkose, Denver and Arapahoe Formations	76	148 - 2,020	238
Laramie Formation	5	448 - 3,680	-
Laramie Formation and Fox Hills Sandstone	20	371 - 1,300	596
Precambrian Crystalline Rocks	5	134 -50,500	-
Chloride (Cl)			
Alluvium	155	0 - 1,400	86
Dawson Arkose, Denver and Arapahoe Formations	109	1 - 385	6
Laramie Formation	9	6 - 3,060	67
Laramie Formation and Fox Hills Sandstone	22	13 - 454	64
Precambrian Crystalline Rocks	8	1 -30,200	3
Hardness ($CaCO_3$)			
Alluvium	147	83 - 1,800	416
Dawson Arkose, Denver and Arapahoe Formations	104	3 - 1,240	40
Laramie Formation	7	6 - 526	24
Laramie Formation and Fox Hills Sandstone	22	3 - 32	9
Precambrian Crystalline Rocks	8	28 -12,700	100
Alkalinity ($CaCO_3$)			
Alluvium	102	35 - 1,402	265
Dawson Arkose, Denver and Arapahoe Formations	76	24 - 385	164
Laramie Formation	7	123 - 558	393
Laramie Formation and Fox Hills Sandstone	22	285 - 569	419
Precambrian Crystalline Rocks	7	16 - 154	105
Iron (Fe)			
Alluvium	64	0.00- 12.7	0.03
Dawson Arkose, Denver and Arapahoe Formations	71	0.00- 6	0.11
Laramie Formation	2	0.11- 4.9	-
Laramie Formation and Fox Hills Sandstone	20	0.00- 1.6	0.10
Precambrian Crystalline Rocks	6	0.00- 31	-

Table 1. (Continued)

Aquifer	Number	Range	Mean
Sodium (Na)			
Alluvium	111	10 - 562	111
Dawson Arkose, Denver and Arapahoe Formations	81	6.2 - 1,050	82
Laramie Formation	7	101 - 2,040	294
Laramie Formation and Fox Hills Sandstone	19	138 - 492	231
Precambrian Crystalline Rocks	5	7.2 -13,700	-
Sulfate (SO_4)			
Alluvium	129	10 - 1,270	200
Dawson Arkose, Denver and Arapahoe Formations	99	0.0 - 1,960	20
Laramie Formation	7	2.5 - 1,960	53
Laramie Formation and Fox Hills Sandstone	22	0.6 - 189	4.4
Precambrian Crystalline Rocks	5	6.2 - 255	-
Nitrate (NO_3)			
Alluvium	97	0.1 - 66	16
Dawson Arkose, Denver and Arapahoe Formations	75	0.0 - 57	0.
Laramie Formation	6	0.0 - 8.5	-
Laramie Formation and Fox Hills Sandstone	17	0.0 - 3.5	0.1
Precambrian Crystalline Rocks	6	0.2 - 222	-
Fluoride (Fl)			
Alluvium	101	0.1 - 8	1
Dawson Arkose, Denver and Arapahoe Formations	76	0 - 4.4	1.2
Laramie Formation	6	1 - 3.6	-
Laramie Formation and Fox Hills Sandstone	18	1 - 10	2.2
Precambrian Crystalline Rocks	7	0.2 - 12	1
Silica (SiO_2)			
Alluvium	88	0 - 109	24
Dawson Arkose, Denver and Arapahoe Formations	79	3.2 - 34	11
Laramie Formation	2	8.2 - 11	-
Laramie Formation and Fox Hills Sandstone	20	8.6 - 20	14
Precambrian Crystalline Rocks	5	18 - 83	-
pH			
Alluvium	128	6.5 - 8.8	7.5
Dawson Arkose, Denver and Arapahoe Formations	96	6.4 - 9	7.9
Laramie Formation	7	7.7 - 8.9	8..
Laramie Formation and Fox Hills Sandstone	21	7.6 - 8.8	8.1
Precambrian Crystalline Rocks	7	6.7 - 7.7	7.1

Source: van der Leeden and others, 1975.

Ground water in the bedrock aquifers is of fair to good quality. Water from the upper part of the Dawson Arkose frequently contains excessive iron and radioactive radon gas. The permeable beds of the Denver and Arapahoe Formations yield fairly soft water with concentrations of TDS ranging from 200 to 1,200 mg/l. The Dawson Group and Laramie Formation contain carbonaceous debris, coal, and soluble minerals; water from such zones contains objectionable amounts of dissolved minerals including iron, hydrogen sulfide, sodium, manganese, chloride, and calcium carbonate. The Laramie-Fox Hills sandstone sequence contains generally good quality water with total TDS concentrations that range from 50 to 800 mg/l. In areas where local geologic structure impedes ground-water circulation, the water may contain troublesome amounts of methane, hydrogen sulfide, iron, and fluoride.

In the vicinity of the RMA, typical ground-water quality is indicated by analyses from an alluvial well and a bedrock well located hydraulically upgradient of the arsenal (Table 2). Both wells are located in Township 3S, Range 66W, Section 17, approximately 0.5 mile south of Fifth Avenue and the extreme southeast corner of the arsenal. The alluvial well (70 feet deep) is an irrigation well, and the well tapping the Denver Formation (depth 269 feet) is used as a domestic well. The dates of the chemical analyses are 1955 and 1958 as reported by McConaghy and others (1964). As shown, water from both the alluvium and the Denver aquifer is high in dissolved solids, but the alluvial water is considerably harder than the bedrock water while the Denver water contains considerably more sodium.

Table 2. Typical Ground-Water Quality in Vicinity of Rocky Mountain Arsenal. [1]
(Concentrations in mg/l, except pH.)

	Alluvial Well	Bedrock Well
Location Number	C3-66-17	C3-66-17
Date of Collection	10-5-55	3-5-58
Silica (SiO_2)	24	11
Iron (Fe)	-	0.07
Calcium (Ca)	51	3.6
Magnesium (Mg)	9.2	0.2
Sodium (Na)	36	92
Potassium (K)	3	0.6
Sulfate (SO_4)	48	2.3
Chloride (Cl)	26	14
Fluoride (F)	1	1.4
Nitrate (NO_3)	8.3	0.0
Boron (B)	0.06	0.04
Dissolved Solids	297	238
Hardness (as $CaCO_3$)	165	10
SAR (Sodium Adsorption Ratio)	1.2	13
pH	7.8	7.8

1) Both wells are located approximately 0.5 mile southeast of the Arsenal in Township 3S, Range 66W, Section 17.

Source: McConaghy and others, 1964

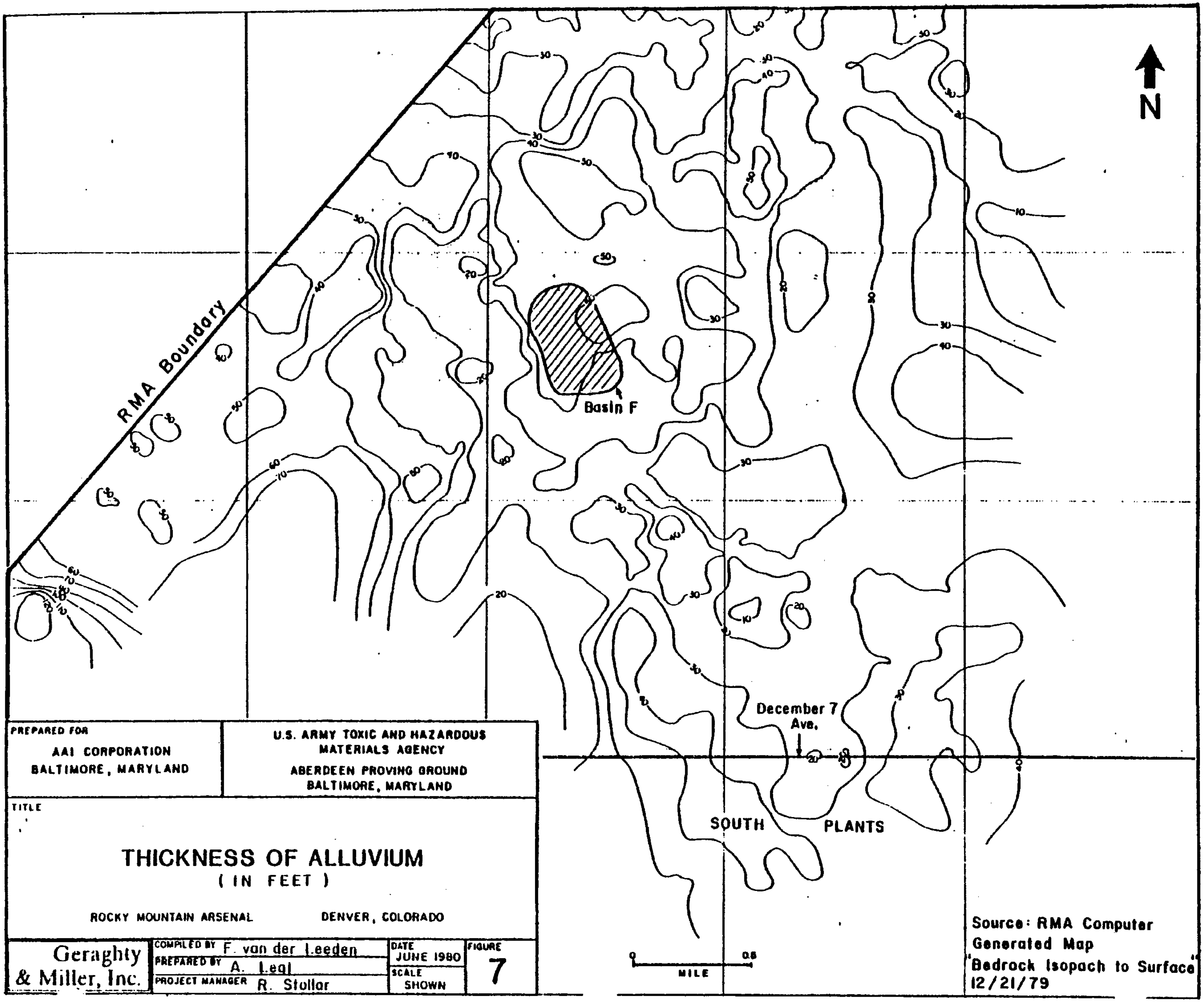
3.0 HYDROGEOLOGY AT ROCKY MOUNTAIN ARSENAL

3.1 Description of Aquifers

Geologic conditions at the RMA have been explored through extensive test drilling carried out in the past. The bedrock, consisting of gray and dark gray carbonaceous shale and claystone of the Denver Formation with occasional dark gray sandstone and siltstone lenses, is overlain by a thin cover of alluvium and windblown deposits. These unconsolidated deposits are made up of silty clay, silt, sand, and gravel. In most places, thin layers of wind-deposited silt and sand cover the alluvium. Almost 1,000 test borings and wells have been installed in order to study subsurface conditions and ground-water quality. Most of these wells were installed to explore the alluvial aquifer. These borings are concentrated in the central and northern portion of the RMA. Few test wells exist in the western, southern, and eastern portion of the RMA.

A map showing the thickness of the alluvium is shown in Figure 7. As may be seen, the alluvial and windblown deposits are 10 to 20 feet thick over most of the RMA. Thick accumulations are found in valleys carved into the bedrock by erosion prior to deposition of the alluvial sands and clays. These valleys represent tributaries of the ancient South Platte River drainage system. The thickness of the alluvium (or depth to the Denver Formation) is about 130 feet in the vicinity of the West Gate.

The Denver Formation represents a typical deltaic deposit with cyclical repetition of silt, clay, and water-bearing sand units. The sands in



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TITLE

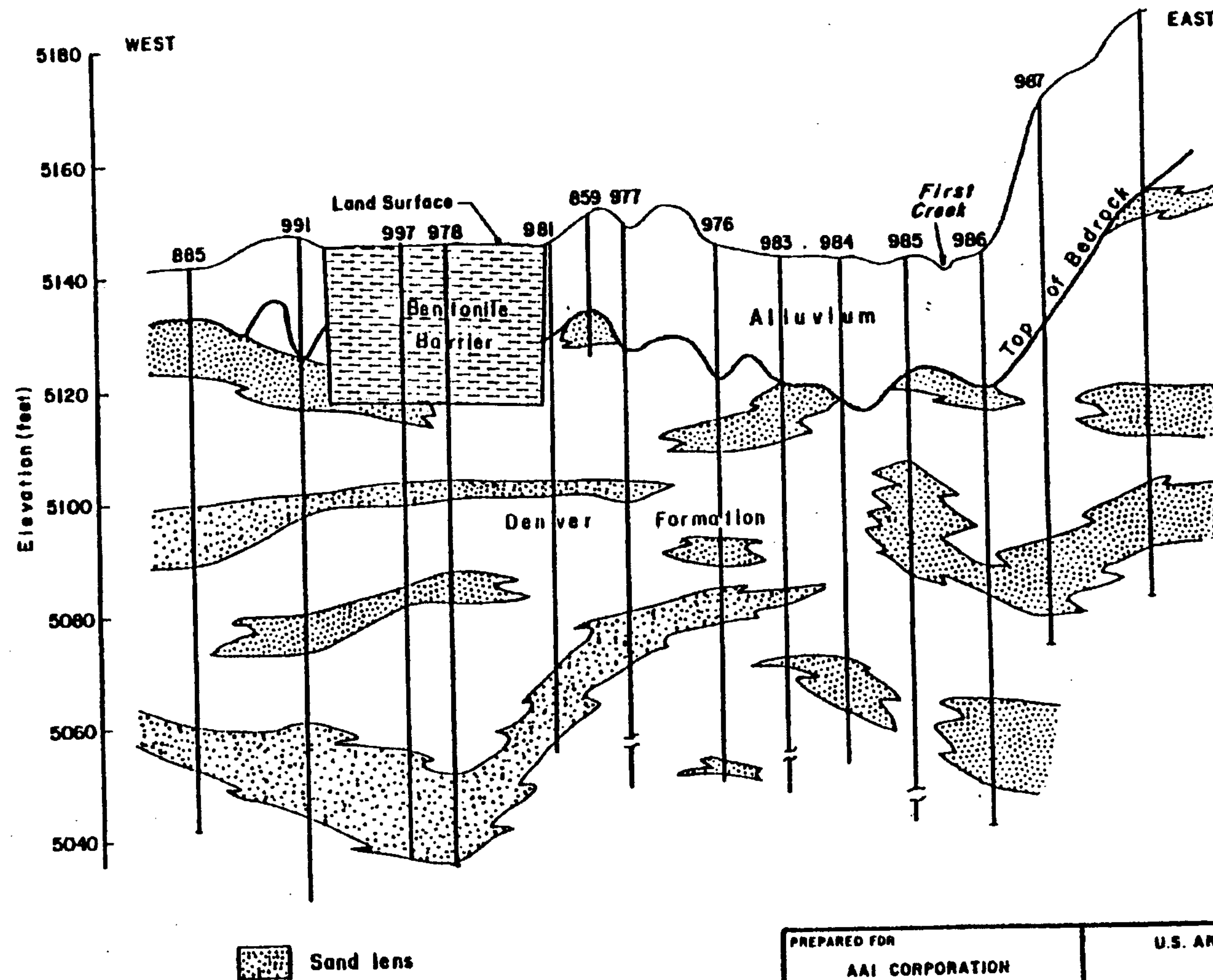
THICKNESS OF ALLUVIUM
(IN FEET)

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY F. van der Leeden PREPARED BY A. Leal PROJECT MANAGER R. Stollar	DATE JUNE 1980 SCALE SHOWN	FIGURE 7

the Denver are lenticular and occupy sinuous channels that are difficult to trace from boring to boring. The stratigraphy of the Denver Formation, particularly the sand beds, was studied in detail along the northern boundary (J. May, 1979). A number of borings along the existing and proposed portions of the bentonite barrier forming the north boundary containment, penetrated a series of channel sands in the Denver Formation. A cross section (Figure 8) illustrates what is believed to be typical Denver conditions. The borings encountered as many as four sands in the upper 100 feet of the Denver bedrock. The thickness of the generally uncemented or poorly cemented and friable sands ranged from a few feet to 20 feet. In places, the sands were found to be well-cemented with a non-calcareous, siliceous cement.

Throughout most of the Denver Basin, the Denver Formation is separated from the underlying Arapahoe Formation by a clay-shale "buffer zone," 75 to 200 feet thick (Romero, 1976). The only borings at the RMA that penetrate the bottom of the Denver Formation are the deep injection well in the vicinity of Basin F and a few of the deep borings located near the north boundary. Comparison of the electric log of the abandoned deep injection well with electric logs of wells elsewhere in the Denver Basin indicates that a shale interval from a depth of 170 to 260 feet in the injection well correlates closely with this "buffer zone." The same buffer zone may also have been encountered in Boring 995 at the north boundary, where a clay-shale zone extends from a depth of 112 to 180 feet.



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TITLE

SAND LENSES IN THE DENVER FORMATION ALONG THE NORTH BOUNDARY

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY F. van der Leeden PREPARED BY A. Leal PROJECT MANAGER R. Stollar	DATE JUNE 1980 SCALE 1" 25'	FIGURE 8

Source: J. , U.S. Corps of Engineers, 1979

3.2 Hydrogeologic Cross Sections

In order to study hydrogeologic and water-quality conditions below the RMA, 11 cross sections were prepared. The procedures for constructing these sections were as follows. First, all test borings deeper than 75 feet were identified; then maximizing the number of deep wells on the section, lines were selected parallel and at right angles to the ground-water flow pattern.

The location of the deep wells and the lines of section are shown on Plate 2. Five sections were constructed in a northwest-southeast direction parallel to the ground-water flow pattern and five perpendicular sections were made in a southwest-northeast direction. In addition, one section was drawn along the RMA south boundary. Construction of the profiles was facilitated through use of the computerized boring-log selection and plotting program designed by James M. Krell (MISO-RMA).

Upon assembly of the profiles, the recorded soil descriptions were converted to relative permeabilities in order to obtain a better understanding of ground-water flow conditions (Table 3). Correlations were then made on the basis of these assigned permeability ratings. The sections show the following information: (a) alluvium/bedrock contact, (b) relative permeabilities, (c) field and laboratory permeabilities, (d) well screen settings and water levels or potentiometric levels in May 1979, (e) water-table elevation, (f) equipotential lines, and (g) approximate direction of the vertical component of ground-water flow.

Table 3. Conversion of Soil Descriptions Into Relative Permeability. [1)]

Unified Soil Classification		Assigned Relative Permeability
Soil Description	Group Symbol	
Well-graded gravels, sandy gravels	GW	High
Gap-graded or uniform gravels, sandy gravels	GP	High
Silty gravels, silty sandy gravels	GM	High
Well-graded sands, gravelly sands	SW	High
Gap-graded or uniform sands, gravelly sands	SP	High
Clayey gravels, clayey sandy gravels	GC	Moderate
Silty sands, silty gravelly sands	SM	Moderate
Clayey sands, clayey gravelly sands	SC	Moderate
Silts, very fine sands, silty or clayey fine sands, micaceous silts	ML	Moderate
Low plasticity clays, sandy or silty clays	CL	Low
Organic silts and clays of low plasticity	OL	Low
Micaceous sults, diatomaceous silts, volcanic ash	MH	Low
Highly plastic clays and sandy clays	CH	Low
Organic silts and clays of high plasticity	OH	Low

Note: The Unified Soil Classification was designed for rapid classification of soils for military construction. It is generally not used for hydrogeological investigations. For purposes of this study, the U.S.C. soil descriptions have been converted into relative permeabilities. Permeabilities assigned to consolidated rocks, such as sandstones, range from low to high; those of siltstone range from low to moderate.

Once the sections were completed, overlays were prepared for each of four water-quality parameters -- namely, chloride, DBCP, DCPD, and DIMP. These are further discussed in the water quality section of the report.

The cross sections confirm the deltaic nature of the Denver Formation as revealed by the alternating clay, silt, and sand beds and reflected by the permeability patterns. As indicated by the alluvium/bedrock contact lines, the alluvial cover is relatively thin (less than 50 feet) in most areas, except in the erosional bedrock valleys and along the western border of the RMA.

The alluvium is 70 to 80 feet thick along the northwest boundary (see Sections V and VI), but reaches 130 feet along the western boundary (see Section VII). The permeabilities of the alluvium vary from section to section. On some sections as much as 50 percent of the alluvial material is classified as highly permeable (Sections I, VI, and VII) but on others (Sections VIII, IX, and X), the highly permeable material makes up less than 10 percent of the sediment. Few deep wells were drilled into the Denver Formation, so the cross sections cannot reveal a great deal of information about the deep stratigraphy. The lenticular nature of the Denver and the resulting variability in relative permeability are best demonstrated on Sections III, IV, and VII, where several wells penetrated several hundred feet into the Denver and correlations could be made. Except along the north boundary (discussed previously), few high permeability sand zones were encountered. Most of these zones appear to be located in the upper portion of the bedrock close to the alluvial contact; however, this probably reflects paucity of information, as lenticular sands in the Denver Formation occur throughout the Denver Basin.

The important feature revealed by the sections is that there is no uniform permeability contrast between the alluvium and the Denver bedrock. In fact, on many sections high permeability zones extend from the alluvium far into the Denver (for example, Sections III, VI, and VII). Moderate and low permeability zones frequently extend across the alluvium/bedrock contact on virtually all cross sections.

The lenticular nature of these high permeability sand zones in the Denver as portrayed on the cross sections can be misleading. These sands appear to be discontinuous lenses -- for example, as shown on Section III, Boring 496 and Section IV, Boring 493 adjacent to Basin F. Yet when viewing this information at right angles on Section VII, it appears that these sand units are actually parts of one continuous channel deposit and extend for at least 3,000 feet. Section VII shows that this high permeability zone merges to the southwest with alluvial material of similar permeability.

3.3 Ground-Water Flow

3.3.1 Methodology

Over 200 wells were used to study and interpret the ground-water flow pattern at RMA supplemented by data from the files of the USGS and Colorado Department of Natural Resources. The wells located on RMA were drilled under varying constraints, both technical and budgetary, and therefore, problems exist in using data from many of them for interpreting ground-water movement. These problems are discussed in more detail in the section on Data Gaps.

To interpret ground-water flow under the Arsenal, wells tapping both the alluvium and bedrock were used. At locations where the alluvium was unsaturated, shallow bedrocck wells tapping an upper sand unit were used. Although this may not be totally accurate, it is the only way of plotting and contouring water levels spacially. Technical problems with combining water levels from wells that tap both shallow and intermediate depths are illustrated on the hydrogeologic cross sections. Therefore, before the general flow pattern under the Arsenal is explained, the vertical flow patterns are discussed.

The geologic description of these cross sections was discussed in a previous section. In order to discuss vertical flow, a cross section should be parallel to a flow line. The south-north cross sections are fairly close to being parallel to such flow lines.

3.3.2 Vertical Flow System

A typical section through the Arsenal in a south to north direction is Section IV (Plate 3). The location of this section is shown on Plate 2. The section runs along the South Plants area, through Basin A, along the west side of Basin F to the northwest boundary. Wells tapping deep, intermediate, and shallow formations are contained in this section. The head (water-level information at different depths) as well as the water-table level was plotted at each well. The vertical equipotential lines were plotted from this information.

In general, the total head in the South Plants area is 5,255 feet above mean sea level (msl) and the total head at the northwest boundary is 5,110 feet above msl, a total head drop of 145 feet in 2.8 miles or a gradient of about 0.0098 ft/ft. This gradient is considered high.

Under the South Plants area, the direction and magnitude of flow is being controlled by leaking water pipes (Zarzycki, 1979, personal communication and McNeill, 1979). Leakage of water from these pipes into a low permeability material has caused a water-table mound to form. The number of years that this mound has been in existence is unknown, but it does control and is a major driving force for flow in the area.

Section IV illustrates the mound and the existing vertical gradient caused by the mounding. Water flowing into the aquifer at the center of the mound would migrate in a vertical direction. This is shown by the equipotential lines. Flow is perpendicular to these lines and movement is from the equipotential line of higher head toward one of lower head. In the southern portion of the mound, water would migrate both vertically and toward Upper Derby Lake; in the northern part of the mound, water would migrate vertically and toward Basin A.

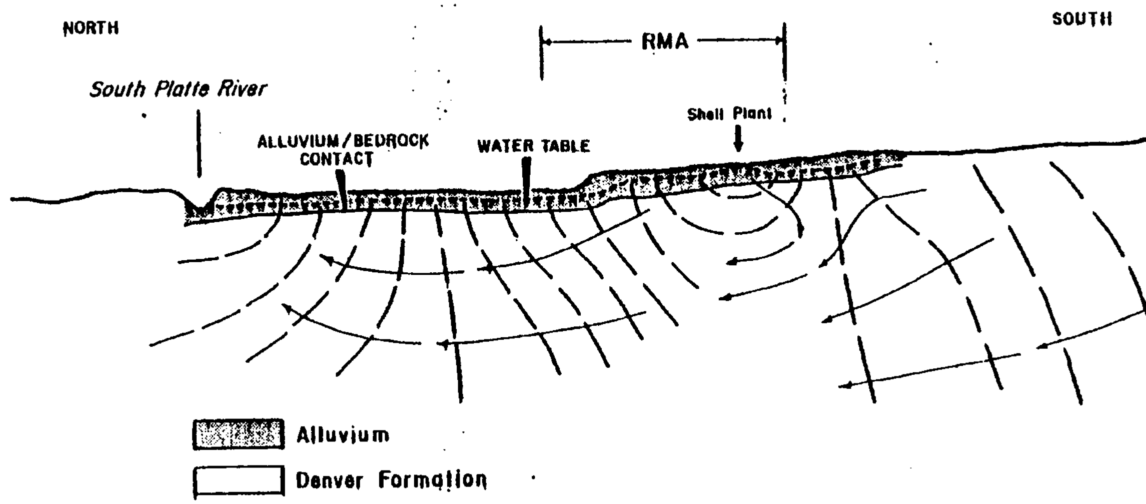
North of the mound, the water table occurs at different locations in the alluvium and bedrock. For example, from Basin A to the Sand Creek Lateal just south of Basin C, the water table exists in the alluvium. However, from the lateral northward to about 'C' Street, the water table alternates between the alluvium and bedrock. North of 'C' Street, the water table occurs in the alluvium. During past programs in this area, wells were drilled to tap only the alluvium; if the water table was not encountered, it was reasoned that ground-water contamination was not a major problem and wells were not deepened into bedrock.

In addition to vertical movement caused by the mound, Section IV illustrates a definite vertical component of flow throughout the Arsenal. This indicates that water from the alluvium can migrate to the deeper formations. During this study, some of the deeper aquifers were examined to determine if heads were higher than the water table. If such occurrences were found, a vertical limit to this type of flow or a bottom to the flow system could have been approximated. However, it was found from the analyses that heads in the deeper formations are lower and vertical migration of water is probably occurring from the upper to lower formations rather than vice versa.

The vertical component of flow can be explained by two hypotheses -- changes in permeability, and the location of the Arsenal in relation to the regional ground-water flow system. In general, flow will change direction when passing from high to low permeability formations. In a regional flow system composed of an alternating sequence of sand and clay, the flow in the high permeability sand will be horizontal and in the low permeability clay almost vertical. The general composite flow system would probably be mapped as what occurs at RMA, a lateral flow system with a major component of vertical flow.

The location of the Arsenal in relation to the regional flow pattern may also be indicative of the vertical flow conditions. In a regional recharge area, water reaching the water table moves downward. If the regional recharge area is in the vicinity of RMA, water entering the water table migrates downward creating a vertical component of flow. As the flow moves towards a discharge area (such as the South Platte River), the equipotential lines (in section) become vertical indicating horizontal flow, and finally, close to the discharge area, the slope of the equipotential lines changes to show the upward gradient of flow. Figure 9 represents a hypothetical flow section in the region of RMA and illustrates this concept. The detailed south to north sections shown on Plates 3 and 4 illustrate similar flow conditions where enough data existed to construct vertical equipotential sections.

West to east cross sections shown on Plate 4 cannot be used in the same manner. Theoretically, if the flow system did not have major vertical components of flow and the section was perpendicular to a flow line (parallel to an equipotential line), the entire section would have the same value of head at all points indicating no flow along the section. However, Section VIII indicates an interesting phenomenon. The flow in the Basin A Neck area, between the two bedrock highs, is almost all vertical. Due to the problems with the well data, the lack of detailed data for interpreting the possibility of leaky sewers, and lack of accurate data to indicate basin leakage, no further explanation can be made of this. However, the interpretation of the cross sections and maps of chemical constituents also point to vertical flow in the Basin A Neck area.



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TITLE

HYPOTHETICAL REGIONAL FLOW SECTION IN THE VICINITY OF RMA

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY F. van der Leeden PREPARED BY A. Leal PROJECT MANAGER R. Stollar	DATE JUNE 1980 SCALE Not to Scale	FIGURE 9

3.3.3 Configuration of the Water Table

To understand the movement of ground water and contamination migration patterns at RMA, the configuration of the water table was estimated and is shown on Plate 5. Under natural conditions, ground water enters the Arsenal as underflow from the southeast and as localized recharge. The water flows toward a major discharge area, the South Platte River, in the northwest. Many previous reports indicate that the flow at the Arsenal is discontinuous; that is, where there are bedrock highs, the alluvium is unsaturated, and the interpretation was that ground-water movement does not occur. This report establishes that ground-water movement occurs in both the alluvium and bedrock. Where permeability decreases in the bedrock, the gradients steepen, and where permeability increases in the saturated alluvium, the gradients flatten out.

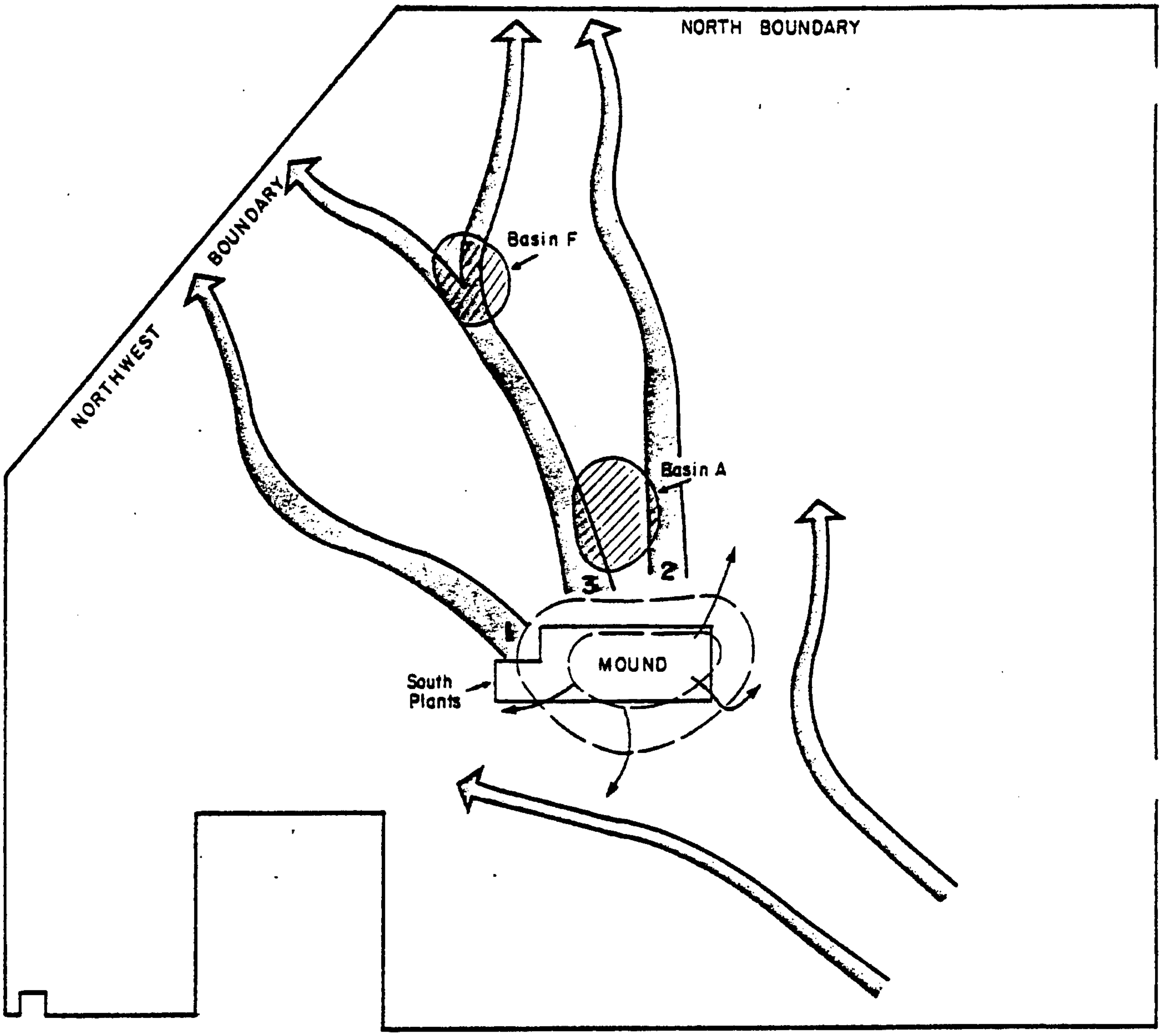
In the southern portion of the Arsenal an anomaly in the water table exists which has dramatically affected the regional ground-water flow pattern through the Arsenal. A water-table mound, approximately 30 feet high, has formed below the South Plants and flow lines radiate from the top of the mound in all directions (Plate 5). A ground-water divide has been created at the confluence between the regional flow system and that of the mound. A ground-water divide is defined as a line where there is no flow, a zone of stagnation where ground-water velocities are zero. This means that water entering RMA from the southeast cannot pass through the South Plants area (flow lines cannot cross), and therefore is forced to turn either east or west. This is shown by the representative flow lines and ground-water divide on Plate 5. Similarly, water from the mound area flowing south is also forced to change direction. As the regional underflow moves away from the mound, flow is toward the west to northwest and the northeast.

For the purpose of illustrating different patterns of contamination migration and to indicate that overall ground-water flow under the Arsenal is a continuous system, the flow regime can be divided into three components (Figure 10).

One section of flow (1) is from the mound and west of Basin A towards the west and northwest boundaries. This flow is bounded by the regional underflow on the south and a limiting flow line (discussed below) in the north. The second section of flow (2) is from the mound and east of Basin A toward the north boundary. This section is bounded by the regional underflow on the east and a limiting flow line to the west. The third major section of flow (3) is from the mound through the Basin A area, through the Basin F area and toward the northwest and north boundaries. This section is also bounded by two limiting flow lines.

The above section describes ground-water flow through the Arsenal in general terms. A more detailed discussion of ground-water flow from the contaminated areas (South Plants, Basin A, and Basin F) to the Arsenal boundaries follows below.

The major flow section through the Basin A area is discussed first because this is the area of major disagreement with previously issued reports.



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TITLE

MAJOR COMPONENTS OF GROUND-WATER FLOW PATTERN ON ROCKY MOUNTAIN ARSENAL

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY	F. van der Leeden	DATE JUNE 1980	FIGURE 10
	PREPARED BY	A. Leal	SCALE	
	PROJECT MANAGER	ROBERT L. STOLLAR		

As Basin A is one of the major sources of contamination, a subregional investigation of the basin was carried out previously without an understanding of the major components of the flow system. The combination of the ground-water mound at the South Plants area, the two bedrock highs west and east of Basin A, and the limited drilling program (depth of wells terminated at bedrock) caused the data to be interpreted incorrectly. It was thought that flow was restricted to the area between the bedrock highs where the alluvium is saturated. The new water-table map shows that the flow pattern between the two bedrock highs is bounded by the two limiting flow lines shown on Plate 5, and it can be seen that flow occurs on either side of these representative flow lines as well.

As flow enters Basin A from the South Plants area, it moves in a north-northwest direction through the Basin A neck to Basin F. Just south of Basin F, major changes in the flow pattern occur as indicated by the equipotential lines. Some of the flow goes west and some northwest. North of Basin F, the flow pattern is very complicated and can only be delineated in a general way as water-table gradients are very flat.

It appears that the permeability and/or saturated thickness increases abruptly north of Basin F causing the equipotential lines to spread out. An attempt was made to decrease the contour interval for more definition but the low water-table gradients, location of data points, and local anomalies (from Basin F leakage?) did not allow better flow definition.

Present data suggest an additional representative flow line from the northeast corner of Basin F to the northern boundary. This indicates that water migrating from Basin A through Basin F or west of Basin F, will continue its path to the northwest boundary. Also, water moving from Basin A to the east of Basin F or just along the eastern boundary of Basin F, will continue to migrate towards the northern boundary.

Basin F and the sanitary and chemical sewers are thought to be sources of contamination; however, the data collection programs initiated thus far to determine the amount of leakage from these sources have been inconclusive. As the mound, Basin A, and possibly Basin F and leaking sewers are major sources of contamination, the ground-water flow patterns indicate that the upper northwest boundary and a small portion of the northern boundary will continue to receive contaminated ground water for a long period of time.

In addition to the flow migrating through Basin A, there is a contiguous flow pattern west of Basin A. Flow initiating at the mound in the South Plants area will migrate toward the northwest edge of Basin A. This flow is bounded on the south by the regional flow system and on the north by the representative flow line which passes through Basin A and continues to the northwest boundary (see Plate 5). It appears that this water is moving very slowly but may become a major source of contamination to the area of the northwest boundary.

The flow patterns east of Basin A are bounded by the regional flow to the east and the Basin A limiting flow line. Contaminated flow from the South Plants area will eventually reach the north boundary of the Arsenal between the two flow boundaries mentioned above and possibly First Creek.

The flow patterns discussed above are important in the study and understanding of migration, however, it should be remembered that the flow pattern shown on Plate 5 is a "snapshot" of the configuration of the water table at one particular time. Any changes in the natural or man-made stresses on the aquifer will change the flow patterns.

3.3.4 Analysis of Flow System

An estimate of the amount of flow and volume of contaminants that are migrating to the boundaries of the Arsenal required a flow net analysis to be carried out. However, due to the complicated hydrogeology and data problems (see Section 6.1), the accuracy of this analysis was so limited that it was not completed. Although the saturated layers and stringers of silt, clay, sand and gravel that characterize the aquifer(s) are considered one flow system, vertical components of flow exist within the system. The materials screened vary in both depth and type. Adjacent wells may be screened at different depths in different materials -- one screen may be set in sand while another is in clay or silt. The vertical component of flow within the system may give head values which differ by a couple of feet. Consequently, equipotential lines may be curved or displaced locally.

Construction of a flow net in this area is therefore difficult with the present data. Flow lines and equipotential lines, which by definition are supposed to intersect perpendicularly, do not, and therefore, construction of the required "curvilinear" square cannot be done accurately.

Hydraulic gradients change throughout RMA. These changes are shown on the water-table map by the various spacings between equipotential lines. In general, areas of low permeability and decreased saturated thickness coincide with tightly spaced equipotential lines, and areas of high permeability and greater saturated thickness coincide with widely spaced equipotential lines.

An additional problem with the flow net analysis is the wide range and discrepancy between permeability values. Permeability values are available from a number of RMA reports and reports by Mitchell (1976) and Vispi (1978). Most of the permeability values were interpreted from slug and falling head tests and a few were obtained from pumping tests along the north boundary. Mitchell's test area is north-northeast of Basin F, approximately 700 feet south of the north boundary. Vispi's test area extended from north of Basin F diagonally northeast to the northern boundary.

Permeability values from Mitchell's report range from 1,500 to 1,590 gpd/sq ft (gallons per day per square foot). Field permeabilities (slug and falling head tests) from this area (1,600 feet west of Well 3, and between 800 and 1,100 feet east and south of Wells 2 and 4) range from 0.3 to 615 gpd/sq ft. However, two field permeability values (slug and falling head tests) from an area 2,400 feet south of Mitchell's Wells 2 and 4 are 2,360 and 5,267 gpd/sq ft.

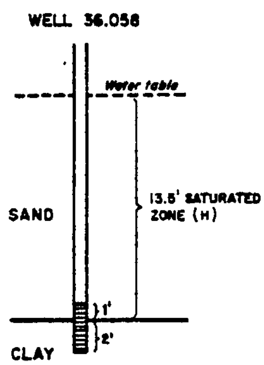
Permeability values from Vispi's report cover a wide range, from 250 to 8,200 gpd/sq ft. However, only four of the 44 wells showed average permeability values of 250 gpd/sq ft. The remainder ranged from 1,100 to

8,200 gpd/sq ft. Although a wide range in values still exists, it is important to note that with the exception of the two high field test values mentioned above (2,360 and 5,267 gpd/sq ft), all other field test (slug and falling head test) values are significantly lower than pumping test values. There are only one or two instances in which an agreement between pumping and non-pumping permeability values exist. Therefore, the permeability values for other areas in the Arsenal as interpreted from slug and falling head tests are suspect, limiting any calculations of flow within the Arsenal.

A problem in the determination of permeability values from slug tests may be the assumptions required by the analytical procedure. The Cooper-Papadopoulos method used to analyze data for wells tapping alluvial deposits assumes radial flow in a confined aquifer. Where partial penetration effects are present, and may be severe, such an assumption may be invalid. For example, Well 36-058 (the shallow well of Boring 706) was open only to the lower 1 foot of the 13.5 feet of saturated material (although this well is listed as having a 3-foot screen, the bottom 2 feet are screened in clay and were disregarded in the analysis - see sketch on following page). The Cooper-Papadopoulos method yielded a permeability value of 2×10^{-3} cm/sec (centimeters per second) for Well 36-058. This is less than that reported for alluvium in the area by Konikow (3.54×10^{-2} cm/sec or 750 gpd/sq ft).

The data for this well were reanalyzed in an attempt to more correctly define the permeability of the aquifer at this location. The method used is one in which the response of an observation well to the sudden removal of a slug of water from a fully or partially penetrating discharge well in an unconfined aquifer is analyzed. A description of the analysis may be found in Section 5.3.1 of Bouwer (1978).

Using the following data obtained from the RMA report:



$$r_c = 0.1 \text{ foot}$$
$$y_o = 3 \text{ feet}$$
$$H = L_w = 13.5 \text{ feet}$$
$$r_w = 0.2 \text{ foot}$$
$$y_t = 1.5 \text{ feet}$$
$$t = 20 \text{ seconds}$$
$$L_e = 1 \text{ foot}$$

and equations 5.43, 5.41, and Figure 5.11 from Bouwer, the effects of partial penetration may be accounted for. These data yield a permeability of 12×10^{-3} cm/sec (254.4 gpd/sq ft), which is six times that obtained by the Cooper-Papadopoulos analysis. This seems to be a more reasonable value.

4.0 CONTAMINATION MIGRATION PATTERNS

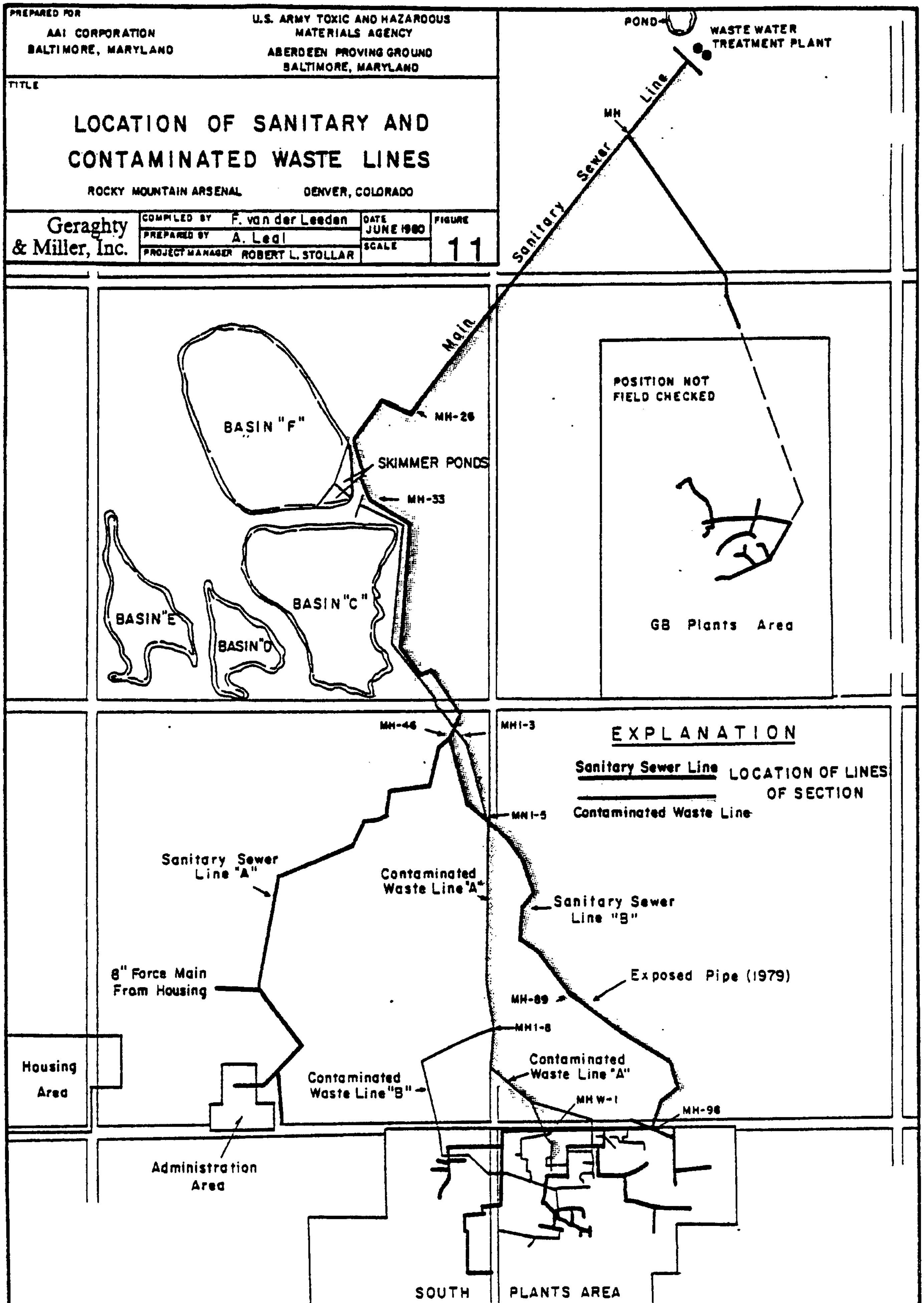
4.1 Sources of Ground-Water Contamination

Actual and potential sources of ground-water contamination on the RMA are numerous and reflect the history of Arsenal operations. Toxic chemical wastes from manufacture and demilitarization of incendiary munitions, pesticides, herbicides, nerve and mustard gases have been stored and disposed of in pits, basins, lagoons, sewer systems, and building drains. Numerous leaks and spills have occurred, and there are numerous isolated sites on the RMA where munitions, equipment, chemicals, and miscellaneous contaminated material were burned or buried or otherwise disposed of.

The South Plants area in Sections 1 and 2 is the prime source of many of the hazardous chemicals that were used in the manufacture of mustard, lewisite, phosgene, white phosphorus, chlorine, incendiary mixtures, hydrazine, pesticides, and herbicides. Wastes from these operations were disposed of in local basins and lime pits in Section 36 as well as in the sanitary sewer system.

Section 36 is considered the most heavily contaminated area in the Arsenal. It contained the original disposal basin (Basin A) which was used from 1942 to 1952. Basin A encompassed roughly 100 acres, and during its lifetime, some 60 million gallons of liquid were dumped there.

With the start of operation of the GB plant in 1952, Basin A was no longer adequate to handle the additional waste material generated. To solve this problem, three natural depressions (Basins C, D, and E) located


PREPARED FOR
AAI CORPORATION
BALTIMORE, MARYLAND
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND
TITLE
LOCATION OF SANITARY AND CONTAMINATED WASTE LINES
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO
Geraghty & Miller, Inc.
COMPILED BY F. van der Leeden
PREPARED BY A. Leal
PROJECT MANAGER ROBERT L. STOLLAR
DATE JUNE 1980
SCALE
FIGURE 11
POND
WASTE WATER TREATMENT PLANT
MH
Main Sanitary Sewer Line
BASIN "F"
MH-26
SKIMMER PONDS
MH-33
POSITION NOT FIELD CHECKED
BASIN "C"
BASIN "E"
BASIN "D"
GB Plants Area
MH-46
MH1-3
EXPLANATION
Sanitary Sewer Line
Contaminated Waste Line
LOCATION OF LINES OF SECTION
MN1-5
Sanitary Sewer Line "A"
Contaminated Waste Line "A"
Sanitary Sewer Line "B"
8" Force Main From Housing
Exposed Pipe (1979)
MH-89
MH1-8
Housing Area
Contaminated Waste Line "A"
Contaminated Waste Line "B"
MH W-1
MH-98
Administration Area
SOUTH PLANTS AREA

in Section 26, were utilized for waste disposal. From 1952 to 1955, Basins D and E were used to receive the liquid waste materials that Basin A could not handle. In 1955, after complaints by local farmers of contaminated ground water originating from Basins A, D, and E off the northwest RMA boundary, construction was begun on an asphalt-lined basin (Basin F). This basin, covering about 93 acres, was completed in October 1957 and has a capacity of 240 million gallons. In the 1957-58 period, the contents of Basin A were pumped to Basin F. At one time Basin F sustained damage to its asphalt liner, and Basin C was used to hold waste liquid during repair operations.

In 1961, a 12,045-foot deep injection well was constructed. Liquid wastes from Basin F were pumped into the well at a rate of several hundred gallons per minute. Deep well injection was discontinued in February 1966 when it was discovered that disposal operations caused seismic tremors in the Denver area. During these five years some 164 million gallons of liquid waste were disposed of in the well.

4.2 Evaluation of Sanitary Sewer and Contaminated Waste Lines

Studies and field observations at the RMA over the last few years have suggested that the sewerage systems may be sources of and/or conduits for the migration of contaminants. Two sewerage systems exist on the Arsenal: a sanitary sewerage system and an industrial waste line. The locations of these lines are shown in Figure 11.

The sanitary system consists of two branches, one originating in the administration area (Line 'A') and the other in the South Plants area (Line 'B'). They merge in the Basin A Neck area and continue north as one line along Basin F and from there northeast to the waste-water treatment plant. In addition, there is a branch that originates at the GB plant and joins the main line about 1,300 feet southwest of the treatment plant. These sewer lines are in use at the present time. The industrial waste line originates at the South Plants area and terminates at the skimming ponds near Basin F. This line carried liquid wastes until March 1978 when discharge to Basin F was discontinued. Although the Shell Chemical Company no longer discharges waste to the line, an estimated 20,000 gpd of infiltrated ground water from the sewer line still enters the basin.

4.2.1 Sanitary Sewerage System

The sanitary sewerage system was the subject of an investigation in 1979 (Black and Veatch, 1979). The entire sewerage system was smoke tested and flow was measured with a V-notch weir in selected manholes. During the smoke testing a few inflow sources and three blockages were located. Flow metering revealed indications of infiltration and exfiltration at different points on the sewer line. In particular, the investigators indicated that there seemed to be infiltration along Line 'B' between the South Plants area and the point where Line 'B' merges with Line 'A'. Exfiltration seemed to be occurring north of this point, in particular along the section of sewer pipe near Basin F.

Visual inspection of the sanitary sewerage system by Black and Veatch revealed that over 24 percent of the manholes in the South Plants area, as well as Line 'B', and the main line to the waste-water treatment plant were in poor condition. Inverts, aprons, and walls were found cracked, and bricks were broken along many sections of the sewer line (the majority of the pipe is constructed of vitrified clay pipe). The most obvious case of disrepair was found between Manholes 89 and 90 where 15 feet of pipe with broken bells was encountered. This particular section of pipe is located in Basin A approximately 1,500 feet north of December 7th Avenue and 1,200 feet east of 'D' Street.

A cross section of the sanitary sewer line was constructed using the survey data from the Black and Veatch report (Plate 6). The section runs from the South Plants area along Sewer Line 'B' and then along the main line to the treatment plant. The water table as of May 1979 was also plotted on this section. Examination of the section shows that the water table was above the sewer line from an area just south of the Plants area in Basin A to the area in Basin A just east of the dry reservoir. In fact, this is in the area mentioned above (Manholes 89 and 90) where pipe with broken bells was observed. Therefore, it is very possible that contaminated ground water is infiltrating the sewer in this area.

Water-level records were examined to determine whether the water table might have been above Sewer Line 'B' in other portions of the Basin A area prior to May 1979. Hydrographs of wells in close proximity to the sewer line were plotted using water-level data stored in the Tier 1 files. These hydrographs are displayed on the cross section. Unfortunately, the period of record is short, but it appears that since December 1978 the water levels in the vicinity of Sewer Line 'B' were at a maximum elevation in late May 1979, the date of the water levels used in the cross section. One well, No. 36-038, with a somewhat longer period of record dating back to July 1978, had a higher water level in the summer of 1978 than at any time during 1979. However, during the period of 1942 through 1952, Basin A was used as a liquid disposal area. At this time the soil was probably totally saturated and ground-water levels were probably above the elevation of the sewer all through Basin A, facilitating infiltration. It can be concluded that infiltration of contaminants from Basin A to the sewer line is probably occurring in the area mentioned above.

It is also likely that the sanitary sewer lines were and still are conduits for certain contaminants that were produced in the South Plants area. The water table is above the sewer lines through much of the South Plants area, and the probability of infiltration of ground water through cracks and holes in the sewer line is high. Sampling of the fluid in the sanitary sewer lines in the South Plants area in Sewer Line 'B' and in the main line to the waste-water treatment plant in the fall of 1979 revealed levels in excess of 300 ug/l of Nemagon in all of these sections (Black and Veatch, 1979). Wells screened below the water table in the South Plants area have levels of Nemagon in excess of 50 ug/l at the present time, but most of the wells in the immediate vicinity of the sanitary sewer lines north of the plant reveal levels below 1 ug/l. Most of the Nemagon in the sanitary sewer lines is probably being transported directly to the waste-water treatment plant where high concentrations of Nemagon have been measured in the pond (McNeill, 1979).

Contamination levels for the first half of 1979 in wells in the vicinity of the sewer line are plotted below the cross section. The wells near the sewer line in the Basin A area contain high amounts of chloride and DIMP, but this is characteristic of the entire Basin A area, and the highest concentration of both of these constituents lies to the east of the sewer line. In addition, DIMP was not manufactured in the South Plants area and is not found in appreciable concentrations in the sewer line itself.

The only wells shown on the cross section (Plate 6) that contained concentrations of Nemagon above the detection limit were No. 26-012, which is at the southeastern corner of Basin F, No. 26-056, located 2,000 feet south of Basin F, and No. 01-020, located at the northern edge of the South Plants area. The latter well reflects the high concentration of Nemagon in the ground water throughout the South Plants area. The detectable amount of Nemagon in the ground water near Basin F may be attributable to a leak in the sewer line, although the sewer line is more than 35 feet above the water table at this point. The only well on the cross section that shows a high concentration of DCPD is No. 36-040 and this level of 687 ug/l is likely attributable to leakage from the section of broken pipe in this area, as discussed below.

Isoconcentration maps of four contaminants and locations of the sanitary sewer lines were examined for possible correlation in order to detect source areas. In general, high concentrations of chloride and DIMP do not show a close correlation with the sanitary sewer lines. High Nemagon concentrations do not correlate with the sewer line position either, but the possibility cannot be totally dismissed that the high concentrations near the north boundary in Section 24 originated from the sanitary sewer line and moved northwest with the ground-water flow. However, it should be remembered that the wells were not located in the areas for the purpose of correlating ground-water contamination and leakage from sewers.

The best correlation was found on the map showing concentration levels of DCPD. High concentrations in excess of 500 ug/l were found in two places below the sanitary sewer line, one along the sanitary sewer pipe that runs along the north edge of the South Plants area and the other directly below the exposed pipe in Basin A described earlier. As in the case of Nemagon, the high concentrations of DCPD near the north boundary in Sections 23 and 24 may be attributable to leakage from the sanitary sewer line in Section 24, but it is more likely that these plumes have another source.

4.2.2 Contaminated Waste Line

The industrial waste line was investigated in June 1960 (U.S. Army Corps of Engineers, 1961). Flow measurements indicated a considerable loss of flow (11.1 percent) between the South Plant area and Basin F. This exfiltration was equivalent to an average of 14.5 gpm or 20,880 gpd. At the time of the survey, considerable leakage was also observed from service lines in the South Plants area.

Plate 7 is a cross section of the industrial (contaminated) waste line (Line 'A') from the South Plants area north to the Basin F skimmer ponds.

The section shows the position of the water table as of May 1979 and the elevation of the sanitary sewer line where it crosses the waste line. As shown, the contaminated industrial sewer lines are at least 3 feet below the sanitary sewer lines where they intersect everywhere north of the South Plants area. In the South Plants area itself, the two systems are often within 0.5 foot of vertical separation.

The water table in May 1979 was above both sewerage systems at several points in the South Plants area and remained above the waste line over a linear distance of 2,000 feet. In the southern portion of the South Plants area (south of the sanitary sewer line), the industrial waste line rises in elevation to about 3 or 4 feet above the water table. In view of the close proximity of the two sewerage systems, their poor condition, and the position of the water table, the probability of ground water mixing with waste fluids and vice versa is high.

North of the South Plants area the water table intersected the contaminated sewer line in the Basin A Neck area. At Manhole 1-3, the water table in May 1979 was 2.5 feet above the sewer line. Immediately north of this point the water-table gradient steepened considerably, dropping 20 feet over a horizontal distance of 500 feet. South of Manhole 1-3 in the Basin A Neck area, the water table was 1.5 feet below the contaminated sewer line in May 1979. The illustration clearly shows that a rise in water table of a few feet would create the conditions required for infiltration into the contaminated sewer line in the Basin A Neck area.

The contaminated sewerage system was not sampled for chemical analysis during the Black and Veatch study. A comparison of the location of the contaminated sewer lines with maps showing concentrations of chloride, DIMP, DCPD, and Nemagon showed no clear correlation between the contamination plumes and the sewer lines.

4.3 Method of Data Analysis

In order to map both the lateral and vertical migration of chemical constituents in ground water at RMA, the horizontal and vertical distribution of four chemical constituents, namely, chloride, DIMP, DCPD, and Nemagon was investigated. As stated in the Introduction, the rationale for selecting these four constituents was as follows. DIMP and DCPD are constituents specifically listed in the cease-and-desist order issued by the State of Colorado. DIMP is a very mobile constituent whereas DCPD is relatively immobile. A study of the distribution of these two chemicals is useful in interpreting differential migration rates. Nemagon (DBCP) is a highly toxic constituent. Chloride, a conservative constituent and excellent tracer, has been mapped during previous studies. Over 300 wells were used to plot concentrations and define contamination plumes both on maps and cross sections.

In addition to the RMA data, information supplied by the Shell Chemical Company also was incorporated. The Shell data consist of water-level measurements and chemical analyses made in 1979 in a series of shallow observation wells located in the South Plants area.

In the following sections, each of the four constituents is discussed separately. First, the map of lateral migration will be described, after which selected cross sections showing significant concentrations of the particular chemical constituent will be reviewed. It should be noted that the values on the maps and cross sections represent maximum reported concentrations as of May 1979. However, in a few areas, data from previous samplings have been used, and these are so indicated. With a few exceptions, the wells used as data points are identical to the ones used for preparation of the water-table map. The total number of these data points is somewhat less than those of the water-table maps as not all of the water-level monitoring wells are regularly sampled for chemical analysis.

4.4 Distribution of Chloride

The distribution of chloride in ground water is shown on Plate 8. The chloride plume is large and major sources of contamination are not easily delineated. However, it appears that Basin A was the major source of contamination.

In the South Plants area, chloride concentrations range from a few hundred mg/l to 600 mg/l. A ground-water mound exists here and it is possible that with time higher concentrations have migrated with the ground-water flow to surrounding areas. Both water-table gradients and chloride concentrations indicate that contaminants may be discharging into Ladora Lake.

There is no doubt that the major concentrations of chloride originated in the Basin A area. Chloride concentrations in the center of Section 36 are as much as 5,000 mg/l. The chloride plume in Basin A covers a considerably larger area than those of other contaminants. The chloride plume extends north into the Basin A Neck area and Basin F with concentrations reaching 5,000 mg/l. From this area, the plume then changes direction with one portion moving toward the northwest boundary of the Arsenal and a second plume extending to the north boundary.

The complicated plume pattern undoubtedly reflects past disposal and control measures. According to Shell Chemical Company and RMA personnel, large quantities of fresh water were diverted to Basin C at some time in the past. This water was subsequently piped to areas north of Basin F for irrigation of wheat. Infiltration of this fresh water may have caused a change in the chloride migration pattern and may explain why chloride values higher than 500 mg/l occur south and west of the limiting flow originating from the Basin A area.

Northeast of the Basin F area, a major chloride plume exists. This plume appears to originate in the northeast corner of Basin F where chlorides reach 2,000 mg/l and could be indicative of a leak in the Basin F liner. Another major plume with a concentration of 2,000 mg/l occurs alongside Basin F, about 800 feet south of the main plume. This might be evidence that Basin F is leaking in two areas.

The chloride plume crosses the north boundary as detected in off-post Wells 304, 305, and 306. The major plume with concentrations of 1,000 mg/l appears to extend less than a half mile across the Arsenal boundary.

At the northwest boundary a similar situation exists, but chloride concentrations are lower at the present time. However, it should be remembered that in former years off-post sampling near the northwest boundary showed chloride concentrations of thousands of parts per million (McNeill, 1980).

The cross sections illustrate the vertical distribution of chloride on the Arsenal. Section X (Plate 21), located south of the South Plants area shows some small plumes at depth. These plumes show concentrations of over 500 mg/l but no major vertical migration of contaminants.

Section IX (Plate 20) in the South Plants area, indicates vertical migration of chloride with values reaching almost 2,000 mg/l (Well 36-058). A portion of the plume is traveling along the ground-water mound towards Ladora Lake.

The situation in the Basin A Neck area is illustrated on Section VIII (Plate 19). The vertical flow section discussed previously indicates a high potential for vertical migration of water between the two bedrock highs of Rattlesnake Hill and the eastern bedrock high. The chloride distribution confirms that such vertical movement has occurred into the Denver Formation. At a depth of approximately 200 feet below land surface, chlorides are 6,300 mg/l.

Section VII (Plate 18) south of Basin F also indicates that chlorides have penetrated to a considerable depth below land surface. Concentrations of 110 mg/l occur in Well 26-135. Comparing both the cross section and the map, it appears that the central part of the plume near Well 26-061 is not a function of leakage from the Basin F area but reflects northward movement of the plume from the Basin A area.

Section III (Plate 14) which passes the South Plants area and the eastern edge of Basin F, bisects the major part of the plume in Section 36. Near Basin F, two major zones of contamination exist with values of chloride above 2,000 mg/l.

Section IV (Plate 15) which runs along the South Plants area, Basin A, Basin C, and the west side of Basin F, displays fairly deep movement of chloride into the ground-water reservoir. Concentrations in the South Plants area range from 40 to 2,000 mg/l. Along Basin B, chloride values are as high as 2,500 mg/l. In the well cluster 26-136, located near the northwestern portion of Basin F, chloride values are as great as 110 mg/l at a depth of 200 feet, 150 mg/l at 150 feet, and 610 mg/l near the top of the water table. Chloride values start to decline in a northward direction and are about 260 mg/l at the RMA boundary.

Section V (Plate 16) which passes through the center of the South Plants area and runs west of Basin A to the northwest boundary, indicates the existence of several separate little plumes in the South Plants area. Whether these plumes were at one time continuous or are discrete and represent different sources is not known presently.

North and northwest of the Basin A Neck area, high chloride concentrations are encountered near Basin E. Values in some wells reach 850 mg/l in

Section 35. North to northwest of Basin E. in Section 27, the chloride values increase to above 1,200 mg/l and indicate some vertical migration with depth.

4.5 Distribution of DIMP

The horizontal distribution of DIMP in ground water is shown on Plate 9. Principal source areas of this chemical appear to be the Basin A area and Basin C where major concentrations occur. Within the central part of Basin A, DIMP values are as high as 10,000 ug/l and below Basin C concentrations are greater than 20,000 ug/l.

The DIMP plume extends across the entire central part of the Arsenal and has moved into the northern part of the Arsenal. The core of the plume with major concentrations appears to be moving from the Basin A area, through the Basin A Neck area to Basin F. At this point, the plume bifurcates with one section moving with the flow lines towards the northwest boundary and another one moving towards and across the northern boundary. The distribution of DIMP below Basin F is unclear and it is possible that Basin F itself is a contributing source as indicated by high (above 1,000 ug/l) concentrations along its northern perimeter. DIMP concentrations in the off-post plume, which extends approximately half a mile across the RMA boundary, are 1,000 ug/l.

The vertical migration of DIMP in ground water is shown on the cross sections. In Section VIII (Plate 19), for example, which passes from west to east through the Basin A Neck area, the DIMP concentration is approximately 1,900 ug/l at a depth of about 200 feet in Well 36-079. Ground-water flow in this section has a definite vertical component, as was discussed in the section on ground-water flow, and the high concentrations of the chemical constituent appears to confirm such a vertical movement.

Cross Section VII (Plate 18) intersects the two separate plumes near Basin F. DIMP concentrations are greatest near the top of the water table with values from a few hundred ug/l to 2,000 ug/l. However, DIMP values at depth range from 2 to over 6 ug/l and show that downward migration has occurred.

Section VI (Plate 17) crosses the widest part of the plume in the northern part of the Arsenal. Values in the shallow screens are as high as 900 ug/l. At depth, the range of concentrations is between 10 and 500 ug/l. This secion shows that DIMP may have moved vertically as much as 100 feet.

Cross Section III (Plate 14) passes through the Basin A plume and intersects the plume again near Basin F. As shown, in the Basin A area, DIMP concentrations are greater than 10,000 ug/l (Well 36-007) and concentrations with depth are also very high. Near Basin F, DIMP concentrations are as high as 1,500 ug/l.

Cross Section IV (Plate 15), which parallels Section III, shows only a small concentration of DIMP near the South Plants area, but intersects the main plume in Section 36. DIMP values range from 2 ug/l in the Basin A Neck area to 17,000 ug/l in the Basin F area. Downward migration of DIMP is indicated as concentrations of DIMP are found 70 feet below the top of the water table.

4.6 Distribution of DCPD

The distribution of DCPD in ground water is shown on Plate 10. The major concentration of DCPD contamination occurs in the South Plants area precisely on the ground-water mound discussed previously.

DCPD concentrations as high as 2,400 ug/l were found on the southern part of the South Plants area and values of 15,000 ug/l were found in the northern part of the South Plants area. The plume of contamination in the South Plants area appears to be segmented. Whether the plumes are right over the original source or whether migration has occurred is unknown. However, based on the flow pattern, the DCPD could now be moving both in a southern, eastern, and northern direction into Basin A. Another plume starts in the Basin A area somewhat east of the dry reservoir and follows the flow lines to the Basin A Neck area. The two plumes indicate that there may have been two major DCPD sources in the South Plants area.

Along the Basin F area there are two apparent sources of contamination. It has been reported that this leakage stems from a ruptured liner in Basin F. The plume in this area has concentrations greater than 500 ug/l. From Basin F the plume then runs almost parallel to the flow lines to the north boundary. Just north of Basin F, DCPD concentrations range from 2,000 to 3,000 ug/l. The plume extends across the north boundary for about half a mile, with concentrations reaching 1,000 ug/l.

Section III (Plate 14) which runs north from the South Plants area along the west side of Basin F, intersects the major plumes and shows that

DCPD has penetrated approximately 30 feet below the top of the water table. Sections IV and V (Plates 15 and 16) illustrate the subsurface extent of DCPD in South Plants area where values are as much as 50 ug/l.

4.7 Distribution of Nemagon

The distribution of Nemagon in ground water is shown on Plate 11. The major area of Nemagon contamination occurs in the South Plants area. Data supplied by the Shell Chemical Company and incorporated on this map indicate a Nemagon concentration of 30,000 ug/l in the South Plants area. This sampling point is Shell Well 26 adjacent to Building 451. By comparing the water-table map and the Nemagon map, it is apparent that this major concentration is near the center of the ground-water mound underlying the South Plants area. Therefore, theoretically, the migration pattern of Nemagon could be in all directions from the South Plants area. However, studying the flow map, it appears that the Nemagon is migrating northward toward the Basin A area.

No excessive values of Nemagon have been detected in the Basin A Neck area; however, further north, another section of the plume appears just south of Basin C. This plume appears to be following the ground-water flow path and moves toward the northwest boundary. Although these plumes seem to be isolated, they could be part of one continuous plume with concentrations in between the plumes below the detectable limit. Another plume of Nemagon occurs along the eastern boundary of Basin F. Whether these concentrations represent leakage from the sewers or from Basin F itself has not yet been determined. This plume originating at Basin F follows the ground-water flow pattern almost perfectly as it migrates towards the north boundary. Several other points of high Nemagon concentrations occur in this plume, for example, along the western boundary of Section 24 where the concentration reaches 36 ug/l. The source of this concentration is unknown. Near the north boundary in Section 24, the plume separates into a northern and northeastern component. The reason for this separation is not known. The plume extends more than 1.5 miles across the north boundary but the concentrations of Nemagon of 4.3 ug/l are not very high compared to those near the source areas.

Sections IV and IX (Plates 15 and 20) appear to be of most interest to illustrate the vertical distribution of Nemagon. Section IV shows that the concentration of Nemagon at the South Plants area (Well 01-011) is as great as 57 ug/l. The section does not bisect the center of the plume where, as mentioned before, concentrations are as great as 30,000 ug/l.

Section IX (Plate 20) running across South Plants area shows that Nemagon has penetrated to a considerable depth. In Well 36-61, a concentration of 7.7 ug/l has been found at a depth of approximately 100 feet below land surface. The section clearly indicates that Nemagon has moved laterally as well as vertically. The 7.7 ug/l value is, however, the only recorded Nemagon reading in this well. Further sampling should be done to confirm this interpretation.

5.0 POTENTIAL CONTAMINANT MIGRATION

5.1 Source Areas and Plume Patterns

Throughout this report various source areas of contamination are discussed. These include the South Plants area, Basin A, Basin F, sanitary and chemical contaminant sewer lines, and various dumps and burial grounds. The next step is to prioritize these sources in relationship to future migration of pollutants. From the analyses carried out, the South Plants and Basin A appear to be the largest areas of contamination.

The South Plants area is not only a major source of contamination but it also overlies the ground-water mound. This mound is a driving force for the ground-water flow system throughout the Arsenal. Therefore, any contamination that occurs beneath the plant will have the potential to migrate to almost all sections of the Arsenal including the west, northwest, east, north, and through Basin A. Presently, there is not enough information available to determine the exact sources or amounts of contaminants entering the ground-water system. However, the contaminants already in the ground-water system will continue to migrate toward the Arsenal boundaries in the future.

Although activities related to future contamination are not occurring in Basin A, the materials buried in the basin, being contained in the unsaturated soils and in the saturated soils will continue to leach or migrate through the ground-water system. The contaminants are of concentrations great enough to be a major problem for years.

The other sources of contamination are not as well defined and therefore their potential for continued contribution of contaminants to the ground-water system cannot be estimated at the present time. However, if Basin F is leaking and is left as is, it presents a source that will continue to add contaminants to the ground-water system in the future. Similar problems will occur from exfiltration of sewer lines and unknown areas that contain buried toxic materials.

5.2 Vertical Migration Through Abandoned Farm Wells

Prior to Federal acquisition of the property in 1942, the land was used for agriculture and stock raising. Water for domestic, stock, and irrigation was obtained from wells, both dug and drilled. As there is a danger that improperly constructed or corroded deep wells could provide passageways for shallow contaminated ground water to move into deeper aquifers, available information on these former wells was examined.

Well records consist of a map showing their location (RMA Drawing 7164-2105), dated April 5, 1943, and an accompanying tabulation of well construction data and depth to water. At the time of the well inventory, recommendations for filling, capping, and/or covering of the wells were made as indicated on the drawing, and marker posts with the well inventory number were installed at each well site. According to these records, a total of 245 wells were inventoried. Of these wells, 181 were capped or covered, 19 were left as is, and 45 were filled in.

According to the drawings, large-diameter dug wells were capped by means of a 2-inch thick wooden cover. Drilled wells were presumably capped with a steel plate welded on the top of the casing, although this is not clearly shown on the drawings. Drilled wells in vaults were first capped on top of the casing and then the vault itself was covered with a 2-inch thick wooden cover. A 3 1/2-foot high wooden barricade constructed of two by fours was erected over each vault. All other wells were identified by means of 2- by 6-inch wooden marker posts sticking up 2 feet above land surface. No information is available regarding the method employed or materials used for plugging or filling of the wellls.

The well inventory lists the depth of only 174 of the 245 wells. Of the 174 wells, 146 were less than 100 feet deep and 28 were more than 100 feet in depth. Of the latter wells, 21 were between 400 and 800 feet in depth, and two were 1,000 feet deep. These deep wells were apparently drilled to the Arapahoe aquifer. Shallow wells tapped the alluvium and the Denver Formation.

The locations of the former farm wells are shown on Plate 22. The well symbols differentiate between wells less or more than 100 feet deep. Letters placed next to the well symbols indicate the reported status of the wells as of 1943: plugged (P), filled (F), or capped (C). By comparing the well locations with the mapped contamination plumes, it appears that eight old deep wells existed within the contaminated area. Available information on these wells is given in Table 4. To investigate whether any of these wells could provide a passageway for contaminated surface or ground water to deeper bedrock units, full details on construction, depth,

Table 4. Record of Deep Abandoned Wells Within Chloride, DIMP, DCPD, and Nemagon Plumes.

Section	Tract	Well No.	Plume	Casing Diameter (inches)	Depth (feet)	Remarks
22	A-49	1	Chloride	6	500	-
	A-49	2	Chloride DIMP	36	524	Concrete
23	A-3	5	Chloride DIMP	-	520	Former windmill well
	A-4	6	Chloride DIMP DCPD Nemagon	6	480	-
24	D-1	6	Chloride DIMP DCPD Nemagon	-	450	Former irrigation well
26	A-59	2	Chloride DIMP	36	700	-
35	A-91	1	Chloride	4	124	-
	A-92	4	Chloride DIMP	6	650	

and sealing procedures, if any, would have to be known. Unfortunately, the available records supply only sketchy information and such an assessment cannot be made.

Efforts have been made over the last few years to locate these deep wells but these have been unsuccessful (Anderson, 1980). Quite likely, well casings or pits have been covered over and no longer extend above land surface. It may be possible to locate these abandoned wells with magnetic detecting gear and removal of overburden. If this were successful, any located wells should be cleaned out, sampled, and properly plugged and sealed using standard well abandonment procedures.

6.0 DATA ASSESSMENT

6.1 Quality of Existing Data

One of the tasks assigned to Geraghty & Miller, Inc. was to assess the extent and usefulness of existing data and to identify the nature of the supplemental data required for subsequent analytical tasks. As discussed before, during this investigation data from many of the wells located at the Arsenal were reviewed and interpreted.

One of the primary problems found when analyzing the well data is related to technical and budgetary constraints. Much of the drilling carried out at the Arsenal was limited to investigating the alluvial formation. Very little information has been developed to determine the interconnection between formations, changes in geologic and chemical conditions as well as changes in head with depth. For this reason, the lower boundary or bottom of the flow system cannot be established.

As pointed out, ground-water flow and contamination migration occur in both the alluvium and the Denver Formation. As little information on the hydrology and water quality is available for the Denver Formation, many data gaps exist throughout the Arsenal. Some of these data gaps will be filled in if the programs summarized below are carried out. However, it is still necessary to analyze the well data, well by well, to determine which information should be kept active and which should be eliminated from the active files. This procedure is also needed to determine where additional wells should be drilled into the bedrock.

Some of the well data was found to be of little use for interpretation of hydrogeologic conditions. For example, examination of screen settings showed that many of the piezometers tapped impermeable coal and clay beds above or below aquifer zones. Water-level and quality information collected from these wells could be misleading for interpretation of ground-water flow and contamination migration. These wells should be eliminated from active data files.

Many of the wells have a long piece of casing (tail pipe) attached to the bottom of the screen to allow for collection of sediment during developing or pumping. In cases where the water table fell below the screen zone and water was retained in the tail pipe, erroneous measurements would occur as the water levels and water samples from these wells are not representative of the ground-water system. Instead, they merely represent standing water in a piece of pipe. During field sampling, the person carrying out the work is not aware of this and as a result, erroneous information becomes part of the active data file.

The general problem related to the entire data collection program at RMA is that the volume of ground-water data being collected is so large and the Arsenal staff is so small that the data cannot be analyzed on a regular basis. Instead, the priorities are to prepare the data for insertion into the RMA data storage and retrieval system. This means that there may be no mistakes in the manner in which the data are written on the form (verification) and yet the data can be completely in error and may not have any relationship to the actual ground-water system. Geraghty & Miller, Inc. recommends that this system of data storage be changed with priority on technical screening of the information before it is stored in the computer. This screening can be done either manually or with the aid of the computer, the objective being to determine if the data are meaningful. If not, a new sample or measurement should be taken to clarify the situation.

Another problem which would occur in any large data-collection program is related to erroneous measurements and mislabeled data. For example, water samples and levels taken at one well will be labeled with a number from another well. In some cases, the measurements were written incorrectly on the coding forms. However, if these data were analyzed systematically, the errors would be assessed quickly.

Wells that have more than one screen opened to different aquifers are not meaningful in a ground-water analysis. Such wells exist, for example, in the Basin A area (Well 35-002, 13 "CP" borings, 10 "RP" borings, and 13 "CO" borings). The representative water levels in these wells are really a composite of heads within all water-bearing zones and the water quality would similarly represent a composite of water quality in different aquifers. Therefore, this information is of little use for a detailed ground-water flow and contamination migration analyses.

When preparing a water-table map or a map illustrating a plume of contamination, these items represent a snapshot of the system at an instant in time. Therefore, the data should really be collected over a small span of time -- a few days at most. Most of the time-related data analyzed during this study represent data collection periods of weeks to months, and in some cases years. This can be misleading and decreases the accuracy of the interpretation. It is recommended that the time-related data, such as water levels and chemical quality, be collected as mass measurements in short periods of time.

As discussed in the section describing ground-water flow, the field permeability tests carried out by using either the slug or falling-head methods have very little credence. There is no correlation between these values and those obtained from the pumping tests carried out by Vispi and Mitchell. Whether the analytical methods themselves are not applicable or whether incorrect interpretations were made cannot be ascertained at this time. However, reviewing permeability data from one well indicated that incorrect assumptions were made. These data were reanalyzed with another method and the results correlated somewhat better with results obtained from the pumping tests. It would be useful to reinterpret some of these field permeability tests to determine if the data can be helpful in further analysis of the flow system.

6.2 Identification of Data Gaps

Ground-water flow and contamination patterns below certain sections of the Arsenal cannot be interpreted because of insufficient data. These areas include the northwest boundary, the southwest quadrant, the entire eastern half of the Arsenal, the Basin A Neck area, and the area south of the Shell Chemical Company plant.

Because of these data gaps, the complete Arsenal-wide ground-water system description cannot be made. For example, the Shell Chemical Company plant, sited over the ground-water mound, a major source of contamination, probably has affected the ground-water quality in the surrounding area. However, at this time, definite conclusions cannot be made using existing data, nor can ground-water flow patterns be mapped in the eastern half of the Arsenal.

In addition to data gaps in large areas, there are also gaps in solving site-specific problems at the Arsenal. These include the following:

- Basin F as a source of contamination. Interpretation of the existing water-level and quality data is inconclusive for determining if Basin F is a major source of contamination and if it is, the amount of contaminated water leaking from the basin.

- Sanitary sewer as a source or means of transport of contamination. The Black and Veatch 1979 studies and our examination of the data indicate a distinct possibility of contaminated ground water infiltration and subsequent transport elsewhere on the Arsenal. Exact locations of infiltration or leakage have not yet been determined.

- Contaminated waste line as a source or means of transport of contamination. No recent engineering studies of the industrial sewer line have been carried out but our analysis indicates a high probability of exfiltration and infiltration. Exact locations of leakage or infiltration have not been determined.

- Flow northwest of Basin F. The flow system just northwest of Basin F cannot be described. This is important as it would aid in interpreting the nature of the contaminant movement to the northwest and north boundaries of the Arsenal and might shed some light on possible leakage from Basin F.

- Flow and transport of contaminants in First Creek and the irrigation laterals. Very little information has been developed assessing the relationship between the ground-water system and flow and contaminant transport in First Creek and the irrigation laterals.

- The lakes south of the Shell Chemical Company plant. Very little information is available related to the ground-water system and the flow and contaminant transport to the south lakes area.

- Regional water quality and flow patterns. The chemical quality of the regional underflow entering the Arsenal from the south cannot be determined. Whether this water is contaminated or not is unknown. Also, its impact on the Arsenal flow patterns cannot be assessed.

- The lower boundary of the flow system (bottom of the flow system). The nature and location of the lower boundary of the flow system either physically or pragmatically cannot be determined.

- Deeper aquifers. It cannot be determined whether the lower aquifers such as the Arapahoe Formation are being affected by the ground-water contamination occurring at RMA.

- Abandoned Farm Wells. Tasks have not been assigned to assess the problems of interaquifer contamination that may be occurring through the abandoned farm wells located in the areas of contamination. No formal effort has been made to locate these wells in the field.

6.3 Regional Work Plans

In order to complete the regional analysis of ground-water flow and contaminant migration, it is necessary to carry out a number of data collection programs. Although these programs are designed for a regional ground-water analysis, they are divided into several subregions only for descriptive purposes. The regional work plans for the northwest bounday, the South Plants and southern portion of the Arsenal, the eastern portion of the Arsenal, and the Basin A Neck area are given below.

6.3.1 Northwest Boundary

As described in the foregoing sections of the report and illustrated on water-table and contamination maps, there exists a definite possibility that contaminated ground water is migrating in a northerly direction toward and across the northwest boundary of RMA. In fact, contaminated water recently has been found at the southern part of the northwest boundary.

At the present time, the number and depths of wells is insufficient to map possible contaminants, the geometry of the plume, and to determine the relationship between the contaminant migration patterns and regional flow. Only after this information becomes available can the seriousness of the situation be assessed and control or containment measures be initiated.

In order to fill this data gap, a drilling and testing program is required. Such a program should be designed to yield the following information:

- The nature, depth and extent of aquifers and confining beds.
- Transmissivity and storage coefficients.
- The nature of vertical hydraulic connection between aquifers.
- The configuration of the water-table or potentiometric surface.
- The ground-water flow pattern, both vertically and horizontally.
- The nature, depth, and extent of contamination.
- The contamination migration pattern.

The following tasks and work description provide further details on the envisioned drilling and testing program.

Task 1. Test Drilling Program

This task should include the following work:

a) Selection of drilling sites and well construction methods.

b) Preparation of drilling specifications and bids, and selection of contractor.

c) Collection of geologic, hydrologic, and water-quality data during the drilling.

d) Field direction of drilling activities.

e) Evaluation of data collected during the drilling program.

f) Preparation of a project memorandum indicating the results of the drilling program and specifying the nature of the required pumping tests needed to determine the relevant characteristics of the aquifer at the site.

In order to collect geologic, hydrologic, and chemical data while drilling, the standard percussion drilling method is recommended. However, the hollow stem auger and rotary methods are other possibilities. Cores should be collected where necessary to define the lithology, permeability, or water quality in low-permeability materials.

Special attention should be given to those differences in geologic and hydrologic parameters that are associated with depth. Geologic samples must be obtained at various depths as each test well is drilled. In addition, water levels must be measured and water samples collected and analyzed so that chemical constituents can also be related to depth. Our experience indicates that this type of investigative technique is absolutely essential in the correct and efficient evaluation of ground-water conditions.

In addition to the required test wells, clusters of three small-diameter monitoring wells may have to be constructed at selected sites. The depth of each well within the cluster should be determined based on the results of the drilling and chemical analyses. For example, one well in the cluster may tap the formation at the water table, the second may tap the middle of the formation, and the third may be drilled to the bottom of the formation. The well clusters will facilitate the determination of differences in head and water quality that occur with depth. This information is required to estimate the geometry and movement of a plume of contaminated ground water.

Collection of water samples should be accomplished by pumping or bailing. Prior to sampling, water accumulated in the well casing should be evacuated to allow true formation water to enter the casing. In low yield wells where bailing may be required, all water should be removed from the well and the water level should be allowed to recover at least once before sampling. In those situations where a well cannot be bailed dry, sufficient water should be removed by pumping.

If the permeability of the formation is so low that water cannot be bailed, or if water quality within a clay layer needs to be determined, special sampling procedures will have to be used. It may be necessary to carry out a geochemical analysis of core samples.

Water samples collected during the drilling will be analyzed by the RMA laboratory. It is assumed that chloride and DIMP can be used as tracers and will be the constituents analyzed for during the drilling program.

Full-time field direction of all well drilling and sampling activities by a trained hydrogeologist is required to make field decisions regarding drilling and sampling depths and to assure the proper collection of scientific data.

It is estimated that approximately 27 test wells will be required to explore the alluvium and Denver Formation along the northwest boundary. The proposed sites for these test wells are shown on Plate 23. The depth of the wells should be determined in the field based on geologic, hydrologic, and water-quality data. For example, if chemical analyses indicate that the plume of contaminated water has been completely penetrated, further drilling at that site should be terminated and well clusters could be installed. This demonstrates the need for quick turn-around time for laboratory analyses.

In addition to the 27 wells, one deeper well should be drilled into the Arapahoe Formation to determine the relationships between the water quality and heads of this formation relative to the upper formations. This well should be constructed by drilling a large-diameter hole (10 to 12 inches) to a major confining layer whereupon the hole should be filled with a bentonite slurry. The next step would be to drill through the slurry to the underlying formations with a smaller diameter hole (4 to 6 inches). This drilling method would prevent cross aquifer contamination. Sampling water quality, geology, and heads should then proceed in a similar fashion as described above. Because of the depth of this well (200 to 300 feet), the rotary method of drilling may prove to be most efficient.

A project memorandum containing a description of the drilling and other data collection techniques, the results of the drilling program, and recommendations for installation of one or more large-diameter production wells and pumping tests should be prepared at the end of this task.

Task 2. Pumping Tests for Aquifer Evaluation

This task will include the following work:

a) Final selection of pumping sites and methods.

b) Preparation of specifications, bid documents, and review of bids for installation of one or more large-diameter production wells, observa- wells and pumping tests.

c) Data collection during the drilling of the production and observation wells.

d) Data collection during the pumping test.

e) Analysis of pumping test data and determination of aquifer parameters.

f) Preparation of a project memorandum indicating the results of the analyses.

At least one large-scale pumping test should be carried out at the site. This pumping test will be designed to provide data required to describe and evaluate transmissivity, hydraulic conductivity, storage coefficient, anisotropic aquifer conditions, boundary conditions, and leakage from confining units.

The pumping or production well should be at least 8 inches in diameter and may be gravel-packed to reduce the development time needed to produce a stable and sand free well. The large-diameter of this well is justified in order for the well casing to accommodate a pump of the proper size and to produce a significant drawdown in the observation wells. The duration of the pumping test must be sufficient for the effects of gravity drainage to dissipate and will probably require a minimum of 72 hours. All water pumped during the test will be diverted away from the well site and observation wells by means of leak-free pipe.

Each observation well used in this test should be of 6-inch diameter so that it can be equipped with a Stevens Type F continuous water-level recorder. Recorders are necessary in order to obtain accurate water-level records over a period of time sufficient to adequately discriminate background fluctuations from barometrically induced changes or other outside effects. As small-scale fluctuations in water levels may be important factors in the analysis, the availability of a continuous graphic record from an automatic recording instrument is essential.

During the pumping test, water samples will be obtained at regular intervals for the chemical analysis required to determine baseline and possible trends in ground-water quality.

Well spacing, construction, and depth of the observation wells will be determined by field conditions and the method chosen for subsequent data analysis. Where the objectives of the test include the determination of the vertical permeability of the aquifers, the method described by Stallman (1971) may be used. This method requires that the pumping well be screened across the entire saturated thickness of the aquifer. Three observation wells would be installed a short distance from the production well. Each observation well would have 5 feet of screen, and one well would be located in the water table, one would be located in the base of the aquifer, and the third would be located midway between. In addition to these three observation wells, another well screened in the middle of the formation would be installed at two to four times the distance between the observation well cluster and the production well. In addition, it may be necessary to install several small-diameter observation wells in the formation below the upper aquifer to monitor water-level behavior. If boundary conditions are anticipated, it would be necessary to install a series of observation wells parallel to these boundaries for better interpretation of test data.

Other nearby wells that fall within the cone of depression during the pumping test should also be measured. All observation wells, whether newly installed or existing, should be tested to ensure that screens are not plugged and that they are open to the aquifer. If the pumped aquifer is confined, it may be necessary to install and operate a recording barograph so that background fluctuation in water-level records can be corrected.

An alternative method for analyzing pumping test data follows a procedure developed by Hantush (Kruseman and DeRidder, 1970). Using this method, a separate curve is constructed to categorize each observation well, and an assumed ratio of vertical to horizontal permeability is used to develop the individual well curves. Field data are then matched to the appropriate curve, and a permeability value is estimated.

Although the techniques mentioned here have been developed for the analysis of unconfined aquifers, there are methods available to analyze pumping tests carried out in confined aquifers.

At the completion of the pumping test, a memorandum should be prepared containing the field data collected and the interpretation of the test results including boundary and recharge conditions. The method of analysis should be indicated in detail along with literature references.

Task 3. Analyses and Evaluation of Different Containment Schemes

After the data is analyzed, a meeting should be held between RMA, WES, USATHAMA, and the ground-water consultant to discuss the various containment methods and objectives. Viable approaches should be selected on the basis of relative effectiveness and costs. These should be subsequently analyzed for thëir impact on the hydrogeologic systems and contamination migration patterns. A project memorandum should then be submitted to the various groups involved, discussing the techniques and results.

Task 4. Preparation of a Final Report

On completion of the various tasks described above, a project report should be prepared that describes the entire investigation. The report should tabulate all data used to develop estimates, conclusions, and recommendations. The report should emphasize the potential impact on the ground-water system and contamination migration patterns caused by, or likely to result from, different selected containment procedures used for the northwest boundary at RMA. It should include recommendations for a ground-water management program and for a monitoring program.

6.3.2 South Plants Area and the Southern Portion of Arsenal

As mentioned throughout the report, very few data exist in the southern portion of the Arsenal. In the area of the ground-water mound and the Shell Chemical Company plant, shallow water-level and chemical data have been collected. However, deep geological, hydrological, or chemical information has not been collected and data in areas to the west, south, and east of the mound, are almost non-existent. For this reason, the interrelationship of the ground-water system with the lakes south of the plant, the regional underflow entering the Arsenal, and the flow patterns and contamination patterns in these areas cannot be defined.

It is recommended that a drilling and testing program be carried out in this section of the Arsenal. The methods of drilling and testing are similar to those described for the northwest boundary program. It is estimated that a minimum of 21 wells are needed. The location of these wells are shown on Plate 23.

6.3.3 Eastern Portion of the Arsenal

A similar data gap exists along the eastern portion of the Arsenal and the ground-water flow and contamination migration patterns cannot be defined. Therefore, a drilling and testing program should be carried out consisting of 15 wells as a minimal effort. The location of these wells are shown on Plate 23. The program of drilling and testing would be similar to the program proposed for the northwest boundary.

6.3.4 Basin A Neck Area

As discussed in the sections describing the hydrogeology, vertical flow and vertical migration of contaminants, the Basin A Neck area is complicated hydrogeologically and also appears to have major components of vertical flow. The available well data are not sufficient to determine or to interpret these occurrences. Therefore, a drilling and testing program consisting of at least six wells should be carried out. The location of these wells are shown on Plate 23. The program of drilling and testing would be similar to the program described in the proposed northwest boundary study.

6.4 Site-Specific Work Plans

Additional data gaps exist at the Arsenal. Although leakage from Basin F is suspected, the drilling and testing work carried out around the basin has thus far not provided conclusive evidence in this regard. As interpreted from the contamination migration maps, it appears that the northeast portion and the central part of the eastern perimeter of Basin F are source areas for Nemagon, DCPD, and chloride.

Existing water-level data do not demonstrate a mounding effect under or along the eastern side of the basin or a change in flow pattern and no data have been collected from beneath the basin. Therefore, a limited testing program along the northeast perimeter of Basin F is recommended.

A few closely-spaced shallow wells, just tapping the water table, are needed to determine whether any mounding efects or changes in the shallow flow system occur. In addition, neutron logs could be run to determine if moisture differences can be determined in the unsaturated zone which might be indicative of leakage.

Lysimeters can also be used for soil-moisture detection. If shallow PVC wells are carefully located, drilled, and developed and neutron logging is carried out, it may be possible to determine the areas and amounts of leakage from Basin F.

In addition to Basin F, information about the relationship of the ground-water system and First Creek should be collected. Shallow wells around the creek can be drilled to determine whether the ground water is effluent to the stream and whether or not the stream is being contaminated by the ground-water system.

Similar information should be developed for the irrigation laterals, sewer lines, and the lakes south of the Shell plant. As these are site-specific studies, it is recommended that separate detailed analyses be carried out using existing data. If these analyses indicate that conclusive interpretations cannot be made, work programs should be prepared to collect the necessary data.

6.5 Ground-Water Monitoring Program

A task assigned to Geraghty & Miller, Inc. was to develop a monitoring program for determination of ground-water flow patterns and contamination migration patterns both on the Arsenal and off-post. During the data collection and evaluation phase, it became evident that many monitoring programs presently exist at the Arsenal. Many wells are being monitored for different sub-programs, for example, there is a North Boundary Study as well as a 360 Degree Program. The numerous monitoring programs encompass water-level measurements and water sampling from wells dispersed over the entire Arsenal. A very large amount of data are being collected and the task of separation and interpretation becomes a difficult one, especially in view of staffing requirements. The logical course of action would be to condense these various monitoring programs into one basic program that would be both manageable in scope and cost-effective. Unfortunately, until RMA, USATHAMA, and Geraghty & Miller, Inc. establish exactly which wells are being used in the present monitoring programs and what the various objectives are, a detailed monitoring program cannot be designed.

Once the monitoring objective is clarified and the reasons for certain programs are understood, a basic plan can be drafted using a minimum of key observation wells and sampling points. Some of the philosophies, objectives, and protocol for establishing a manageable monitoring program are given below.

6.5.1 Monitoring Objectives

The reason for monitoring and the constituents which have been monitored have changed with time as new information has been obtained and new objectives have been imposed. At the present time, monitoring objectives should include the following:

- Assure compliance with regulations covering the quality of ground water leaving the Arsenal.
- Observe lateral movement of contaminants as a function of time.
- Observe vertical movement of contaminants with time and changing hydrologic conditions.
- Observe changes in contaminant concentrations within monitored areas as a function of time and any imposed abatement conditions.
- To confirm that treatment or containment systems are effective.

- To detect new sources of contaminants.
- To predict the composition and concentration of contaminants that will require future treatment at each treatment location.
- To determine the time at which treatment/containment systems are no longer required.
- To determine whether surface-water quality is threatened by ground-water contamination.
- To determine the hydrologic characteristics of the section of aquifer being sampled.

6.5.2 Monitoring Well Selection

Selecting wells for monitoring must be done in a way that insures that data from each well will be meaningful and will contribute to the overall description of ground-water contamination. The following criteria should be applied to the process of choosing wells that comprise a permanent monitoring system.

- Construction details must be known.
- Wells with an historical data base should have high priority.
- The well must sample only the section of the aquifer open to the screen.
- Locations must delineate known zones of contamination.
- Locations must include enough outlying wells to detect new contaminants.
- Locations must provide regional water-level and water-quality coverage.

The most important single feature of a well designated as a permanent monitoring point is knowledge of its construction. Details such as the screened interval, lithology of the aquifer in the screened interval, sealing and finished depth should be obtained from well records. Results of water quality analysis cannot be integrated into the overall picture if the spatial relationship of the sampling location is not known.

If several wells nearby each other are eligible for permanent monitoring point designation, the one or ones having a prior sampling history should be picked. A fundamental purpose in monitoring is to generate information that will provide trends and a predictive ability. The longer the period of record, the more significant the analytical data becomes.

Tracing the movement of contaminants at the Arsenal requires a three-dimensional array of data. Thus, a geographical spread of wells must be coupled with the proper distribution of screen depths. Because the chemical data will be plotted horizontally and vertically, the ground water comprising the sample should be representative of the screen zone and not a composite of an undefined aquifer thickness. This condition will be met if the screen zone is properly sealed.

Wells chosen as permanent monitoring points must be responsive. That is, to the degree possible given the permeability of the aquifer, there must be a free exchange of water. Wells can become clogged with corrosion, microbial growth, or fine sediments in the well screen and thereby give false water elevation readings and anomalous samples.

Sampling points are required to predict excursions of contaminants across the Arsenal boundaries, to measure the efficacy of pumping and treating rehabilitation systems, to measure contaminant movement within the Arsenal, and to detect any new contaminants from internal or external sources. Using the criteria discussed above, the well locations chosen will meet these objectives.

6.5.3 Contaminant Criteria

There are a number of criteria on which to base the choices of contaminants to be analyzed for. These include several that are scientifically based in addition to the legal criterion. The legal criterion is easiest to deal with as it specifies the constituents which must be quantified and it may also require a certain sensitivity of analysis. Wells along the Arsenal boundaries are subject to the regulatory requirements and will automatically be subjected to the prescribed analytical protocol.

Quantifying chemical constituents, especially organics, is more accurately and easily done when the constituent in question is present in a concentration several times greater than the detection limit. When several constituents are present, but are not all required to accomplish the monitoring requirements, those in highest concentrations should be selected. For inorganic substances, this rule applies universally as each substance requires a separate analysis. Organic compounds, on the other hand, are analyzed in groups according to their requirements for work-up and gas chromatographic (GC) analysis.

The analytical requirements are such that organic compounds must be grouped according to analytical techniques. Volatile compounds are separated from the aqueous matrix by the purge and trap method. Detection may be by an electron capture detector for chlorinated compounds or by flame ionization for non-halogenated compounds. Non-volatile compounds are separated from the aqueous medium by extraction with organic solvents. There may be a pH adjustment of the water according to the class of compound being analyzed for. The same array of GC detectors are used for these compounds as for the volatiles. The organic group having the highest concentration, or the one having the least complicated analytical protocol combined with quantifiable concentrations, should be chosen for routine analysis.

The behavior of the contaminant in the subsurface is another factor in determining the constituents to be included in the analysis of ground water in a given area. Generally, volatile, low molecular weight compounds are more mobile than compounds of higher molecular weight. Therefore, the more mobile substances are likely to be present at greater distances from the known or potential contamination source. DIMP, for example, is a compound which is mobile and has been shown to undergo negligible sorption on soil particles.

The discussion up to this point has been directed toward limiting the analytical effort to constituents which will show meaningful trends without including the whole spectrum of possible compounds. Probably on an annual basis, or possibly biannually, a comprehensive analysis will be required. This analysis would include known contaminants and scans to detect new constituents. With the organic constituents, this is not particularly difficult as each GC procedure detects a class of compounds. Inorganic constituents must be determined individually, so each constituent requires a decision regarding its probable presence or identification of a source that will justify its inclusion.

6.5.4 Sampling Procedures

The predominant reason for sampling a monitoring well is to collect ground water representative of that in the screened zone of the aquifer. There is a rigorous protocol which must be followed to achieve this end. Its components include pumping procedures, use of appropriate types of equipment, and procedures for making physical and chemical measurements in the field.

The depth to water should be measured prior to pumping or bailing the well. It should also be measured again following sampling unless the well has been pumped dry. These measurements will provide data with which to construct a water-table map. It will also show how responsive the well is and provide an indication of the permeability of the aquifer.

If a well is capable of yielding water, it will be filled with a column of water extending from the water-table or piezometric elevation to the bottom of the well. Only the water in the screened zone or open hole, in the case of rock, is in contact with water in the aquifer. The remaining water is isolated from the aquifer and is in contact with the atmosphere and the well casing. These conditions lead to changes in water chemistry ranging from subtle to gross. The degree of change may not be easy or possible to quantify, but the standing water assuredly is not equivalent to that in the aquifer.

The first task in sampling is to remove the standing water. This allows a sample to be freshly withdrawn from the aquifer for collection. Researchers with the U.S. Environmental Protection Agency (USEPA) recommend removal of ten times the volume of water standing in the well casing (Pettyjohn and others, 1980). If the well can be readily pumped, this guideline should be followed. However, monitoring wells frequently do not yield adequately enough to allow continuous pumping, or the water table is below suction limit and bailing is required.

When the well is bailed or pumped dry, it may be sampled upon recovery. If bailing is required, and the well yields adequately, many dozens or even hundreds of bailer volumes may be required to evacuate ten times the volume of standing water. Under these conditions, removal of three volumes of water is usually adequate. This is true particularly if the water is withdrawn from the top of the water column. As water is removed, fresh aquifer water flows in from the screen zone and moves up the water column displacing the stagnant water. The most important point of this evacuation procedure preceeding sampling is to precisely repeat the procedure each time the well is sampled (Gibb and others, 1980). Frequently this part of the protocol is specific to each well according to its characteristics.

Devices used to collect ground-water samples must not be allowed to carry contaminants from well to well or to introduce contaminants from their own construction. Pumps, hoses, and bailers must be carefully cleaned between samplings, or each must be dedicated to a well.

Hoses of Teflon or silicone rubber are best suited for sampling because of their inertness. Table 5 lists materials suitable for well sampling in order of preference. Teflon and silicone rubber are expensive

Table 5. Materials Used in Sampling Ground Water for Organic Compounds in Order of Preference (Pettyjohn, and others, 1980).

Glass

Teflon

Stainless steel (not for DDT)

Polypropylene

Polyethylene

Other plastics and metals (Tygon may leach plasticizer)

Rubber

(over $1.00 per foot), so budgetary constraints may dictate a material such as polyethylene. If the ground water to be sampled is known or suspected of being heavily contaminated, slight sorption losses on the hose may be tolerated. Conversely, if low part per billion or lower concentrations are to be quantified, the most sophisticated techniques and materials are called for.

Ground water is in a equilibrium with the minerals of the aquifer, and usually supports a lower concentration of dissolved oxygen than does surface water. Withdrawing ground water exposes it to atmospheric contact. The water immediately undergoes a gaseous exchange with the atmosphere. Oxygen is dissolved and gases such as carbon dioxide and hydrogen sulfide may be evolved from the water. This exchange changes the oxidation potential of the water and may result in pH or conductivity changes from induced chemical reactions.

For the reasons cited above, measurements for pH, Eh, dissolved oxygen, and specific conductance must be made in the field on freshly withdrawn samples. Measurements of dissolved oxygen and Eh, moreover, should be made in flow-through cells or on flowing water to eliminate changes resulting from water contacting the atmosphere.

Sample containers should be carefully cleaned with detergents and organic solvents prior to use. Containers for volatile organic analysis are usually closed with a silicone rubber septum top and must be filled leaving no air space. Samples for other analytes are collected and chemically preserved according to standard procedures as outlined by USEPA or the laboratory. If transportation of samples requires more than 24 hours, cooling and chemical preservation may be required.

Most of the contaminants of concern at RMA are organic compounds. Pettyjohn and others (1980) report on specific sampling techniques for organic compounds. This report mentions an all-glass submersible pump developed at Rice University. A more rugged submersible pump that fits a 2-inch or greater diameter casing is available from Leonard Mold & Die Works in Denver. It was developed by Middleburg of the USGS and is available in a plastic or stainless steel housing. Both of these pumps operate with compressed gas. In the Middleburg pump, the gas inflates bladders, so it does not contact the water and should not strip any volatile organic contaminants.

When using a submersible pump or a suction pump and hose, water should be withdrawn from the top of the water column if it is above the screen. If the water table is in the screen zone, the well should be pumped from the bottom to evacuate stagnant water in the tailpipe. If the water table is below the screen and water is only in the tailpipe, no sample should be collected. This water is not representative of aquifer water.

Permeabilities appear to vary widely across the Arsenal. Resulting ground-water velocities vary from fast to extremely slow. Unless data for developing trends or specifications for treatment are required on a more frequent basis, quarterly to annual sampling should be appropriate. The quarterly samples would be for selected key constituents and the annual sampling would be for a more comprehensive analysis. Wells near the boundary may be constrained to a sampling schedule set by a regulatory agency, or in the case of the northwest boundary, by the influence of a pumping public supply well. The time of travel of contaminants from inner monitoring wells to the border will also influence the selection of sampling intervals.

7.0 IMPACT OF BASIN F CONTAINMENT SCHEMES ON THE GROUND-WATER FLOW SYSTEM

7.1 Introduction

As discussed previously, contaminant migration in the vicinity of Basin F appears to be controlled by ground-water flow. This flow is oriented in both the north and northwest directions and exits the Arsenal at both its north and northwest boundaries.

In order to restrict contaminants from exiting RMA, various containment procedures near Basin F were conceptualized by USATHAMA. To determine the impact of these containment procedures on ground-water flow, a numerical model was used to simulate the ground-water system. The model first simulated the present flow conditions and then was used to estimate changes in head and flow as caused by the proposed containment procedures. Only flow was modeled, no movement of contaminants was simulated.

The different containment schemes as conceptualized by USATHAMA that were modeled include:

Scheme 1. A full-depth impermeable bentonite clay barrier completely surrounding Basin F. It is assumed the barrier will be anchored in the first low-permeability bedrock formation.

Scheme 2. Dewatering wells placed along the northern margin of Basin F to form a dewatering "trough" to intercept contaminated ground water; treatment of the water to remove contamination, and reinjection of the treated ground water downstream of the trough. Pumping and teatment would continue until Basin F is evaporated and/or reclaimed and the ground-water contaminant levels reduced to an aceptable level.

Scheme 3. Placement of a low-permeability bentonite slurry wall to the north of Basin F, and operation of dewatering wells on the upgradient side of the wall, with subsequent treatment and reinjection on the downgradient side of the wall. Pumping and treatment would continue until ground-water contamination was reduced to an acceptable level.

Scheme 4. Placement of a low-permeability bentonite slurry wall to the north of Basin F, and operation of dewatering wells upgradient of the wall and along the west side of Basin F. Reinjection of the water would take place outside the modeled area. Pumping and treatment would continue until ground-water contamination was reduced to an acceptable level.

The techniques for estimating input data and the results of the modeling effort are described below. This modeling effort should be considered as preliminary because the data defining aquifer geometry and coefficients had to be either estimated or assumed.

7.2 Description of Numerical Model

A finite-difference model was used to simulate the flow conditions of the study area. The model used for this study is the basic aquifer simulation program modified for water-table conditions as published by the Illinois Water Survey (Prickett and Lonnquist, 1971). The model is a numerical approximation of the differential equation using the finite-difference technique to define lateral movement of ground water in a non-homogeneous aquifer under existing boundary and initial conditions.

In order to simulate the ground-water regime, hydrogeologic data are input to the model. These data include aquifer geometry, water-bearing characteristics of the aquifer, head distribution within the flow system, recharge to and discharge from the aquifer, and boundary and initial conditions. Simulation is achieved once the head and flow relationships within the field area are duplicated by the model. Calibration of the model was carried out by matching the flow regime described by the May 1979 water-level configuration map.

Once calibrated, the model was used to simulate and forecast the probable head and flow relationships likely to occur as a result of stresses imposed to the ground-water system. In this case, these stresses are due to the implementation of different contaminant containment schemes, including discharge wells, recharge wells, and impermeable or low-permeability bentonite clay barriers. In order to forecast these changes, it is assumed that future precipitation and recharge patterns will, on an average basis, remain unchanged. Thus, future aquifer recharge of the ground-water regime occurs uniformly at the average annual rate. The model estimates the apparent ground-water impact for an area of approximately 7.8 square miles (2.18×10^8 square feet) in and around Basin F.

To discretize the data used by the model, the aquifer was divided into a grid composed of squares. The columns are vertical lines, numbered from west to east from 1 through 24; the rows are horizontal lines, numbered from north to south from 1 through 17. The size of each nodal area is 800 by 800 feet (Figure 12).

Because the model distributes time and space within a finite-difference mesh (or grid), it assumes that flow lines within each grid are parallel to one another. This is valid with the exception of areas near pumped nodes. At a pumped node, flow lines are not parallel and converge towards the pumping well. Therefore, correction factors must be applied to the areas around the pumped node if it is to accurately represent head and flow relationships. The correction techniques used in this model include converging flow near pumped wells in relationship to grid size and grid design. The method is described by Prickett and Lonnquist (1971).

7.3 Ground-Water System Description

A description of the ground-water system on which the model is based includes the definition of the hydrogeologic units, the geometry of the flow system, aquifer characteristics, boundary conditions, and the stresses on the system. With these data, the model can be constructed, tested, calibrated, and used to forecast the probable head and flow changes within the aquifer. The system description is based on available data, published reports, and field testing carried out at RMA. Some of the basic information has been described in previous sections of this report. Assumptions and estimates of additional data are given below.

7.3.1 Boundary Conditions

The area modeled encompasses Basin F, and extends a minimum distance of 5,200 feet in all directions around Basin F (Figure 12). Although natu-

EXPLANATION

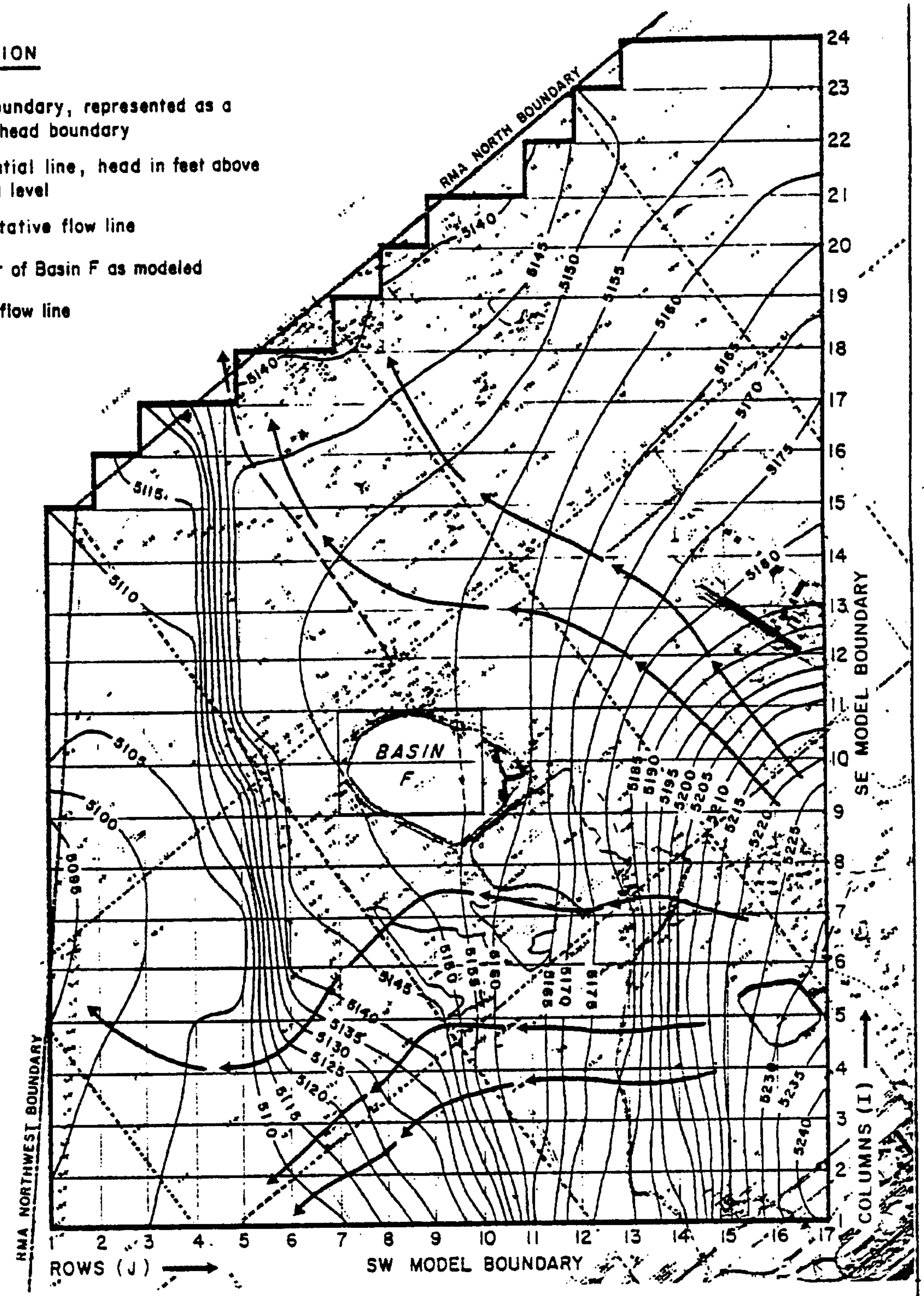
Model boundary, represented as a constant head boundary

—5150— Equipotential line, head in feet above mean sea level

Representative flow line

BASIN F — Perimeter of Basin F as modeled

Limiting flow line



800

0 1000 2000 3000 4000 ft.

COMPUTER GRID BOXES ARE 800 ft. x 800 ft.

PREPARED FOR AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

TITLE

SIMULATED WATER-TABLE CONFIGURATION FOR CALIBRATION WITH MAY 1979 DATA

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY	MICHAEL DE CILLIS	DATE JUNE 1980	FIGURE 12
	PREPARED BY	WILLIAM H. CICIO	SCALE SHOWN	
	PROJECT MANAGER	ROBERT L. STOLLAR		

ral hydrogeologic boundaries are not encountered in the modeled area, model boundaries are imposed on the system.

The model is bounded by: (1) RMA's north boundary property line; (2) RMA's northwest boundary property line; (3) a predetermined southeast model boundary line; and (4) a predetermined southwest model boundary line. All model boundaries are simulated as constant-head boundaries. That is, it is assumed that heads at the boundaries are not affected by the modeled aquifer stresses and thus will not change significantly. All aquifer stresses are to be implemented directly at, or near Basin F, and the constant-head boundaries are at distances too remote for water levels to be affected by the Basin F containment schemes.

The boundaries are indicated by the heavy lines which form regular and irregular patterns around the modeled area (Figure 12). The model was developed to compute the flow leaving the Arsenal's north boundary. In addition, the model was designed to compute the flow into or out of the other three model boundaries. These flows were then summed with the total recharge and discharge to the system in order to develop a water balance. The water balance is used as a check to determine if all water leaving or entering the model is accounted for.

7.3.2 Aquifer Characteristics

As the type and thicknesses of saturated materials vary through the modeled area, permeabilities and their associated transmissivities vary too. Thus, the major assumption made for the modeling procedure was that the average horizontal permeability of the different types of saturated layers remains constant. Therefore, the horizontal permeability values used by the model were calculated by vertically integrating the individual permeability and thickness values for the different layers of saturated materials.

As discussed in the flow section of this report, there is a vertical component of flow and the model can only simulate horizontal two-dimensional flow. Therefore the saturated thickness of the ground-water flow system and the bottom of the water-table system had to be determined. A practical bottom of the modeled system was selected to be 200 feet below land surface as a drop of water traveling from the top of the water-table to 200 feet would take many tens to hundreds of years. It is assumed that a thickness of 200 feet would aid in the vertical averaging of the coefficients.

Using the cross-sections along Basin F prepared by Geraghty & Miller, Inc. (Plates 3 and 4), vertically integrated permeability values were calculated for all borings on the cross-sections. The calculations were based on the following:

- The type of saturated material -- alluvium, Denver Sands, clays.
- The associated permeability of each material.
- The thickness of the saturated layer.

Permeability values for the three basic types of saturated materials vary from unit to unit, as well as within each unit. Thus, average permeability values used were as follows: (1) alluvial materials: 750 gpd/sq ft

(Konikow, 1977); (2) Denver Sands: 30 gpd/sq ft (RMA reports); (3) clays: 0.21 gpd/sq ft (RMA). Again, the permeability value assigned was dependent upon the percentage of the saturated alluvium, Denver Sands, and/or clays within the aquifer. These permeability values were then multiplied by the saturated thickness to calculate a vertically integrated transmissivity value. These integrated transmissivity values were then entered as data into the model.

7.3.3 Aquifer Recharge

Recharge to the system occurs from infiltration or precipitation. The amount of rainfall infiltrating into the subsurface and entering the aquifer system was simulated in accordance with aquifer conditions. An estimated recharge rate of 0.2 ft/year based on published reports (Geraghty & Miller, Inc., 1979) was used for an initial attempt. During model calibration it was found that the computed heads were too high, and therefore, recharge was reduced to a value of 0.1 ft/year. The computed heads from the reduced recharge rate matched their aquifer conditions. This is further discussed in the section on model calibration.

The recharge rate was uniformly distributed throughout the modeled area, with the exception of Basin F which was modeled with zero recharge. As Basin F contains a low-permeable liner, it was assumed that any precipitation falling within the basin would contribute negligible recharge to the ground-water system.

7.3.4 Pumpage

Removal or pumpage of ground water requires simulation as it is a stress on the aquifer system. The only pumpage in the model area is along the north boundary where a few gallons per minute is being pumped and subsequently treated and recharged on the other side of the bentonite barrier.

Pumpage outside the Arsenal's boundary, if constant, is compensated by the constraints on the flow system. That is, if the computed internal head distribution matches the observed May 1979 head distribution under steady-state conditions and fixed heads at the boundaries, the model is simulating the ground-water system and the stress upon the system.

7.4 Model Calibration

The objective of model calibration is to match computed head with observed head distributions within the modeled area. This is generally demonstrated by using the model to simulate the ground-water flow system during a period where model outputs can be compared to observed water-level data. If the difference between observed and computed water levels exceeds tolerable limits, the input data and/or coefficients are modified to obtain the best match between observed and computed data. The model was run, and an attempt was made to duplicate the May 1979 water-table map compiled by Geraghty & Miller, Inc. and shown on Figure 13.

The data related to aquifer geometry, coefficients, recharge and boundary conditions discussed previously, were input to the computer. The numerical technique then solved the equations that describe the head and

EXPLANATION

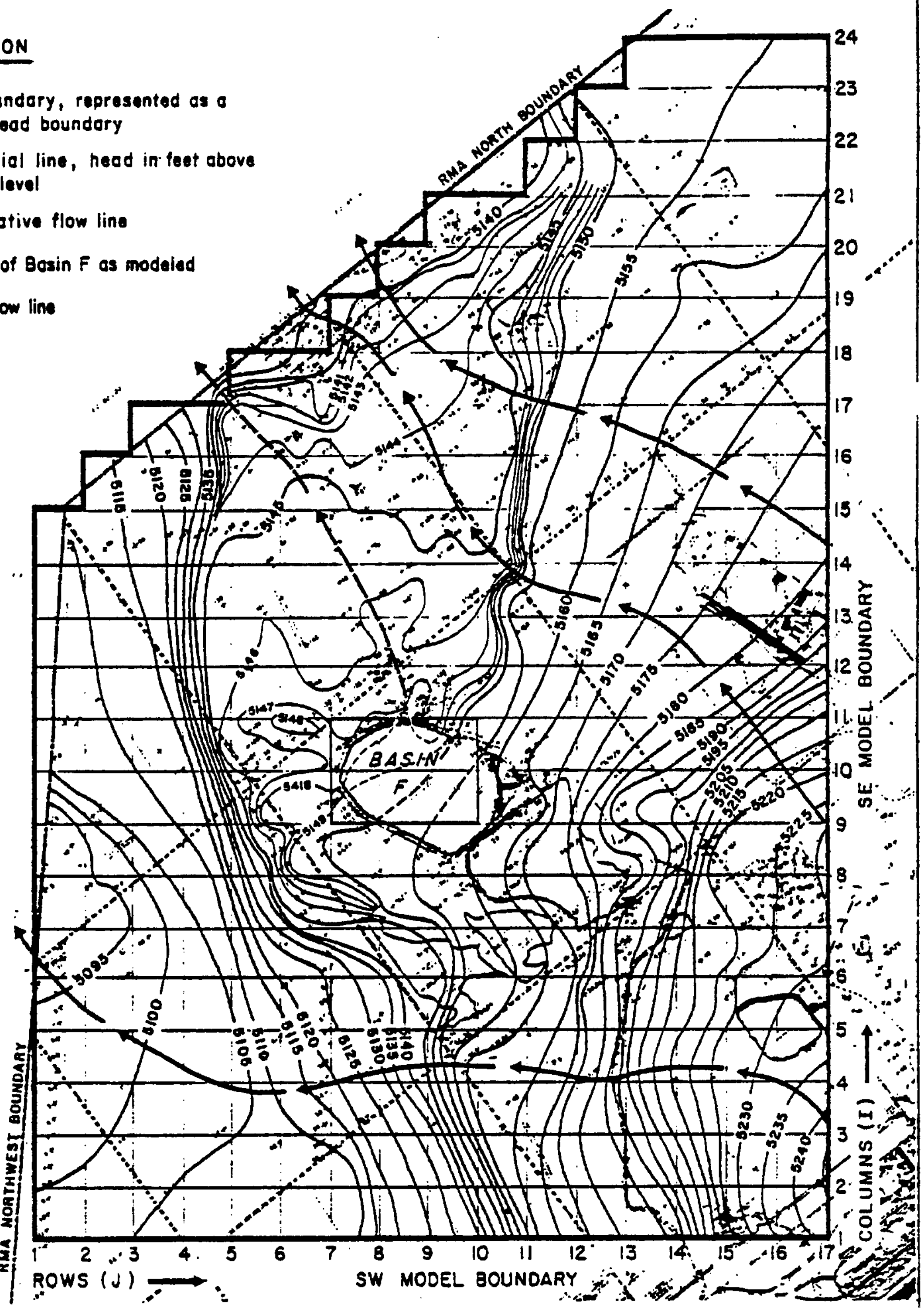
Model boundary, represented as a constant head boundary

—5150— Equipotential line, head in feet above mean sea level

Representative flow line

BASIN F — Perimeter of Basin F as modeled

Limiting flow line



800

0 1000 2000 3000 4000 ft.

COMPUTER GRID BOXES ARE 800 ft. x 800 ft.

PREPARED FOR AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

TITLE

CONFIGURATION OF THE WATER TABLF FOR MODELED AREA, MAY 1979

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY	MICHAEL DE CILLIS	DATE JUNE 1980	FIGURE
	PREPARED BY	WILLIAM H. CICIO	SCALE SHOWN	13
	PROJECT MANAGER	ROBERT L. STOLLAR		

flow conditions within the aquifer. In this case, the model was used to solve steady-state conditions within the aquifer. Under steady-state conditions, the flow system is in equilibrium with recharge and discharge and therefore there is no change in storage. It is therefore necessary for all stresses on the system to remain constant. The solution for this simulation occurs as a distribution of heads within and the flows either into or out of the modeled area.

In general, comparing the computed and observed water-level maps as shown on Figures 12 and 13, the computed water levels were comparable to the observed May 1979 water levels. Approximately 50 percent of the computed water-level elevations were within 1 foot of the observed elevations; 70 percent were within 3 feet, 80 percent were within 5 feet, and 90 percent were within 7 feet. It is believed that had more study time been available, the calibration results would have been significantly improved.

Although calculated heads at individual nodes may vary from the observed, the flow system has been duplicated by the simulation model. Flow across the model moves, in general, from southeast to northwest and exits the Arsenal along the north and northwest boundaries. Flow through the Arsenal is continuous but where it migrates through thick sequences of clay or bedrock (Denver Formation) gradients steepen as permeabilities decrease. In contrast, where ground water flows through high permeability material, such as alluvial sands, the gradients flatten.

In both the simulated and observed flow systems, a limiting flow line originates from the Basin F area extending from the northeast corner of Basin F to the northern boundary. This indicates that water originating upgradient from the Basin A Neck area (situated between the two bedrock highs) flowing under Basin F or west of the Basin F limiting flow line, exits RMA at both the northwest, and a corner of the north boundaries. Flow migrating from the Basin A Neck area moving on the east side of that same limiting flow line exits the Arsenal solely at the north boundary.

As previously mentioned, part of the simulation procedure involved the calculation of flow across the model boundaries. Flows leaving or entering these boundaries are listed in Table 6. Outflow across the RMA north boundary is computed to be 322,460 gpd (approximately 224 gpm); outflow across the RMA northwest boundary is 497,600 gpd (approximately 346 gpm); outflow across the model southwest boundary is 67,189 gpd (approximately 47 gpm); and inflow across the model southeast boundary is 441,610 gpd (approximately 307 gpm). Therefore the total outflow as underflow from the modeled area is 887,249 gpd and the total inflow (underflow into the modeled area plus recharge from precipitation) is 888,180 gpd; indicating a water balance within 0.1 percent. It should be noted that these flows are based on the best approximation of permeability and recharge values as derived from the data base.

7.5 Results of Simulation

The purpose of the various containment options developed by USATHAMA is to control ground water at a rate equal to the natural flow and to treat and inject this water in such a manner that minimal impact is created on the ground-water flow system. Four different containment schemes near Basin F were simulated and the results are discussed below.

7.5.1 Scheme 1 - Full-Depth Barrier Around Basin F

The model was used to simulate a full-depth impermeable bentonite clay barrier completely surrounding Basin F. This was accomplished by creating a no-flow boundary around the perimeter of Basin F. A no-flow boundary is simulated by assigning zero permeability and transmissivity values for the nodes simulating the aquifer underlying Basin F as described by Prickett and Lonnquist (1971).

Figure 14 shows the head and flow relationship that resulted from simulation. It is evident that the system has not changed much as compared to the calibrated run (Figure 12). Flow patterns are very similar, as are the computed heads. The impact on the system from the full-depth barrier can be determined by comparing the calculated flows across the Arsenal and model boundaries with the calibrated flows (Table 6).

It is evident that the full-depth barrier creates a minimal impact on the system. Flow rates changed, as shown on Table 7, as follows: (1) outflow across the Arsenal's north boundary increased by 4,170 gpd (1.3 percent); (2) outflow across the Arsenal's northwest boundary decreased by 2,800 gpd (0.6 percent); (3) outflow across the model's southwest boundary decreased by 4,148 gpd (6.2 percent); and (4) inflow across the model's southeast boundary decreased by 4,410 gpd (1 percent). Thus, it can be concluded that the impact imparted by the full-depth impermeable bentonite clay barrier on the ground-water flow system is very small.

Table 6. Simulation of Containment Schemes at Rocky Mountain Arsenal, Denver, Colorado -- Boundary Flows.

	Containment Scheme	Net Withdrawn From System in gpd (Recharge-Pumpage + Injection)	Flows Out Of or Into Boundaries of Model, in gpd			
			RMA North	RMA Northwest	Model Southwest	Model Southeast
	Model Calibration	-446,570*	322,460	497,600	67,189	-441,610
1.	Full-depth barrier around Basin F	-446,570*	326,630	494,800	63,041	-437,200
2a.	Dewatering and injection (40 gpm)	-446,570*	333,790	495,020	59,347	-442,450
2b.	Dewatering and injection (51.4 gpm)	-446,570*	336,170	494,290	57,536	-442,390
3.	Dewatering and injection of 40 gpm with slurry wall	-446,570*	345,110	492,360	52,234	-443,220
4.	Dewatering of 70 gpm with slurry wall (no injection)	-345,770**	296,830	483,610	29,015	-459,250

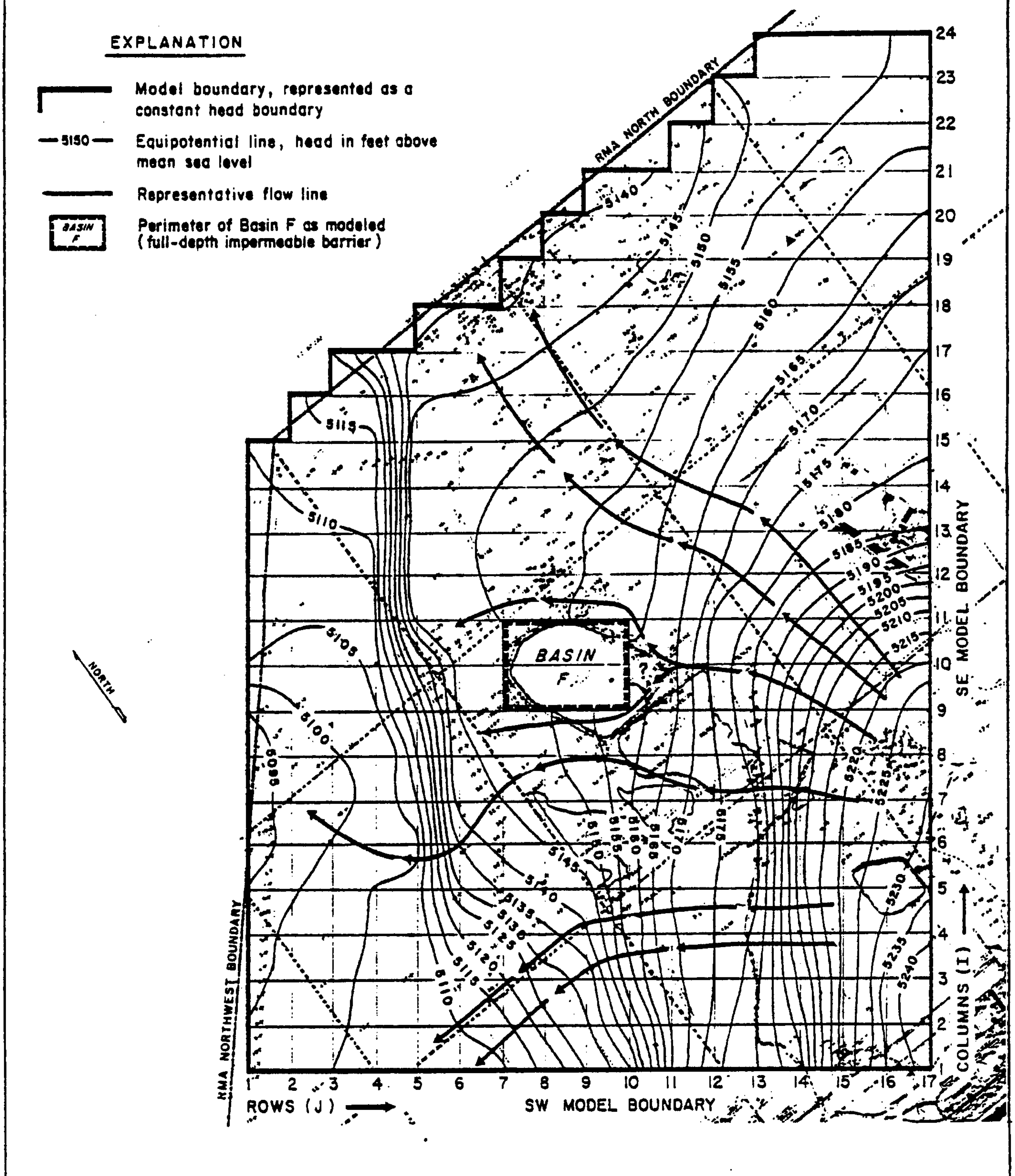
* Water balance accounted for at least 99.7 percent of water in system.
** Water balance accounted for only 98.7 percent of water in system.

Note: A negative sign in front of a value signifies flow into the system, a value without a sign (positive) signifies flow out of the system.

Table 7. Simulation of Containment Schemes at Rocky Mountain Arsenal, Denver, Colorado -- Change in Boundary Flows.

Containment Scheme	Change in Flow Out Of or Into Boundaries of Model, in gpd			
	RMA North	RMA Northwest	Model Southwest	Model Southeast
1. Full-depth barrier around Basin F	4,170 increase (1.3 percent)	2,800 decrease (0.6 percent)	4,148 decrease (6.2 percent)	-4,410 decrease (1.0 percent)
2a. Dewatering and injection (40 gpm)	11,330 increase (3.5 percent)	2,580 decrease (0.5 percent)	7,842 decrease (11.7 percent)	-840 increase (0.2 percent)
2b. Dewatering and injection (51.4 gpm)	13,710 increase (4.3 percent)	3,310 decrease (0.7 percent)	9,653 decrease (14.4 percent)	-780 increase (0.2 percent)
3. Dewatering and injection of 40 gpm with slurry wall	22,650 increase (7.0 percent)	5,240 decrease (1.1 percent)	14,955 decrease (22.3 percent)	-1,610 increase (0.4 percent)
4. Dewatering of 70 gpm with slurry wall	25,630 decrease (7.9 percent)	13,990 decrease (2.8 percent)	38,174 decrease (56.8 percent)	-17,640 increase (4.0 percent)

Note: A negative sign in front of a value signifies flow into the system, a value without a sign (positive) signifies flow out of the system.



PREPARED FOR	
AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

TITLE

CONTAINMENT SCHEME 1 — SIMULATED WATER-TABLE CONFIGURATION

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY	MICHAEL DE CILLIS	DATE JUNE 1980	FIGURE
	PREPARED BY	WILLIAM H. CICIO	SCALE	14
	PROJECT MANAGER	ROBERT L. STOLLAR	SHOWN	

7.5.2 Scheme 2 - Dewatering Wells and Injection Wells Near Basin F

In order to determine the pumping rate for this scheme, a hydrogeologic cross-section along the north side of Basin F was analyzed. The section, as discussed previously, indicates that the formation contains low-permeability material. Also, from the cross-section, the thickness of saturated alluvial material available to be screened by a production well was determined. Using this thickness as a guideline for the amount of obtainable drawdown available to the well, it was determined that a maximum theoretical pumping rate of 10 gpm per well was possible. This 10 gpm per well was pumped from four wells, spaced 800 feet apart along the northern side of Basin F. The same 10 gpm rate was injected back into the aquifer through four recharge wells located 2,400 feet downgradient (northeast) from the pumping wells (Figure 15).

Figure 15 shows the head and flow relationship that resulted from simulation. The overall flow regime of the modeled area is not changed, however, locally around Basin F, major changes in head and flow did occur.

The discharge wells create a pumping "trough" which extends from the center of Basin F northward and eastward, where it joins the cone of impression created by the recharging wells. Within this area around Basin F, flow paths have been re-oriented and flow is toward the pumping wells. Water migrating downgradient from the Basin A Neck area towards Basin F is directed to the pumping "trough." In addition, the recharging wells cause the flow, originally moving toward the Arsenal's north boundary to be reversed. Flow is now toward the Basin F pumping "trough" and a local

EXPLANATION

Model boundary, represented as a constant head boundary

—5150— Equipotential line, head in feet above mean sea level

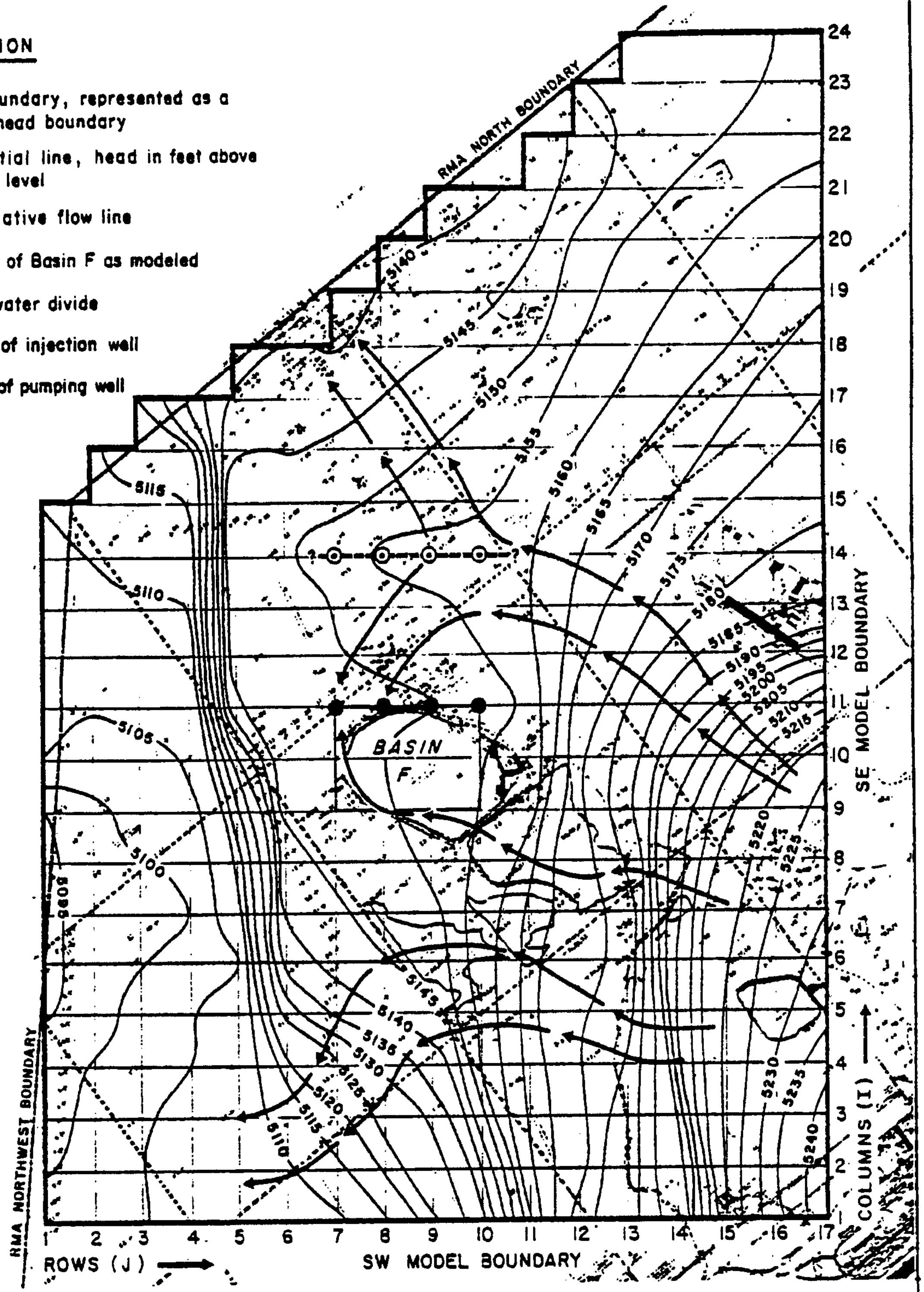
Representative flow line

BASIN F — Perimeter of Basin F as modeled

Ground-water divide

Location of injection well

Location of pumping well



Note

Pumping and injection rates = 10 gpm per well.

800 0 1000 2000 3000 4000 ft.

COMPUTER GRID BOXES ARE 800 ft. x 800 ft.

PREPARED FOR AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

TITLE

CONTAINMENT SCHEME 2 — SIMULATED WATER-TABLE CONFIGURATION

(PUMPING AND INJECTING A TOTAL OF 40 GPM)

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY	MICHAEL DE CILLIS	DATE JUNE 1980	FIGURE 15
	PREPARED BY	WILLIAM H. CICIO	SCALE SHOWN	
	PROJECT MANAGER	ROBERT L. STOLLAR		

ground-water divide has been established.

Flow across the Arsenal and model boundaries is somewhat affected but does not adversely impact the overall flow system when compared to the calibrated flows (Table 6). Injection of the previously pumped and treated waters increases the flow across the Arsenal's north boundary by 11,330 gpd (3.5 percent). Further evidence for this change in the flow as caused by pumping is shown by the decreased outflow across the Arsenal's northwest and southwest boundaries and the increase in flow across the model's southeast boundary. Compared to the flows computed in the calibrated simulation (Table 7), the decreased flows are computed to be approximately 2,580 gpd (0.5 percent) and 7,842 gpd (11.7 percent), respectively, and the increased flow is about 840 gpd (0.2 percent).

Because the underflow north of Basin F may be more than 40 gpm and it may eventually be necessary to capture the entire underflow, another simulation was carried out. Darcy's Law was used to calculate the flow by using the heads and gradients established by the calibrated run. Flow into each node in both the model's column and row directions was summed. The flow to the pumping nodes was computed to be approximately 14.2, 16.2, 12.5 and 8.5 gpm for a total of 51.4 gpm. This quantity of water was then fairly equally distributed to the four injection wells in the following manner: 12.9 gpm for Wells 1 through 3 and 12.7 gpm for Well 4.

Figure 16 shows the head and flow relationship that resulted from pumping and injecting at the above rates. The overall flow system of the modeled area is quite similar to the previous pumping and injection plan.

EXPLANATION

Model boundary, represented as a constant head boundary

—5150— Equipotential line, head in feet above mean sea level

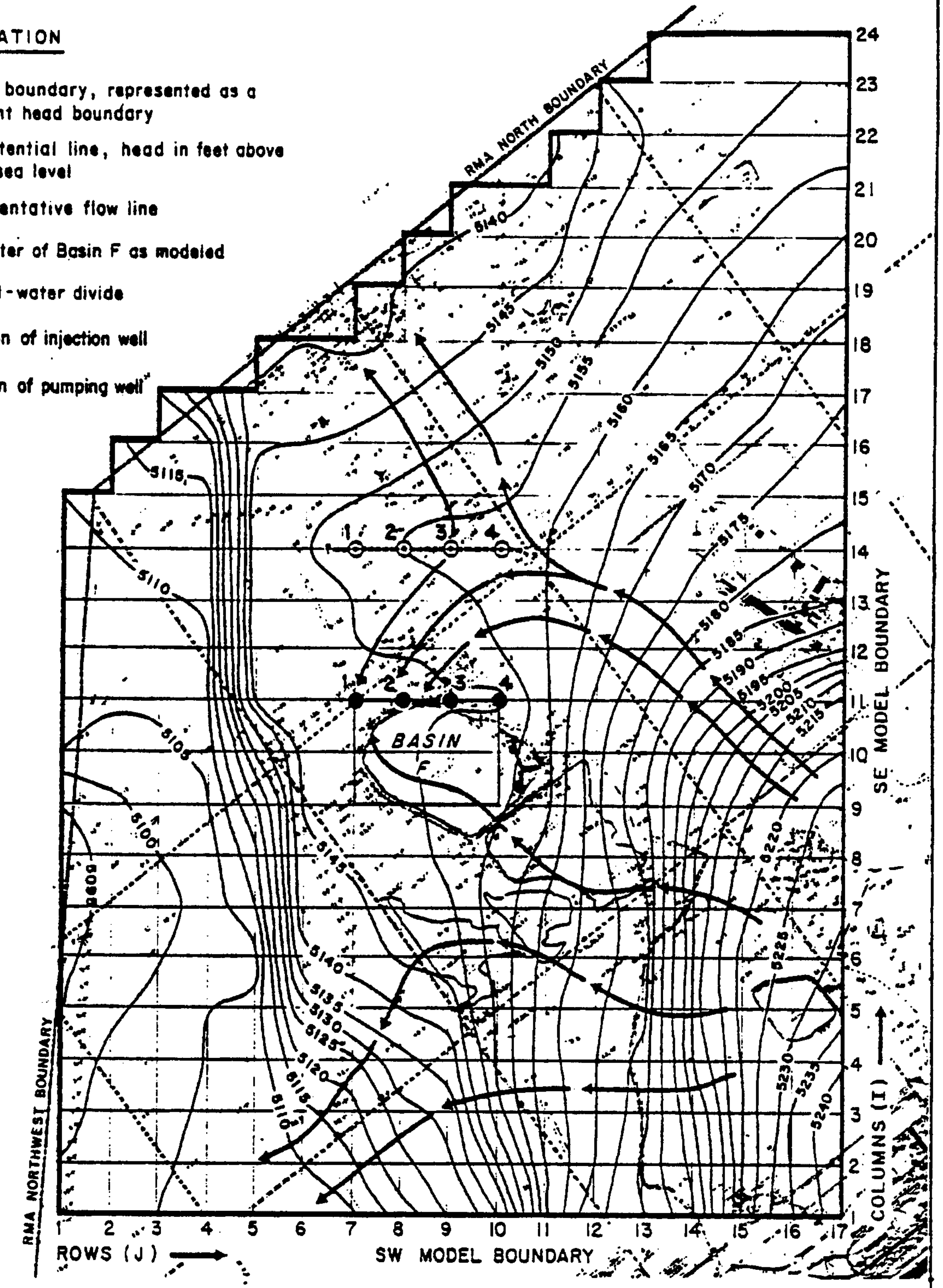
Representative flow line

Perimeter of Basin F as modeled

?---------? Ground-water divide

1 ⊙ Location of injection well

1 ● Location of pumping well



PUMPING WELLS

Well No.	Rate (GPM)
1	14.2
2	16.2
3	12.5
4	8.5

INJECTION WELLS

Well No.	Rate (GPM)
1	12.9
2	12.9
3	12.9
4	12.7

800

0 1000 2000 3000 4000 ft.

COMPUTER GRID BOXES ARE 800 ft. x 800 ft.

PREPARED FOR

AAI CORPORATION
BALTIMORE, MARYLAND

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

TITLE

CONTAINMENT SCHEME 2 — SIMULATED WATER-TABLE CONFIGURATION

(PUMPING AND INJECTING A TOTAL OF 51.4 GPM)

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.

COMPILED BY	MICHAEL DE CILLIS	DATE JUNE 1980	FIGURE 16
PREPARED BY	WILLIAM H. CICIO	SCALE SHOWN	
PROJECT MANAGER	ROBERT L. STOLLAR		

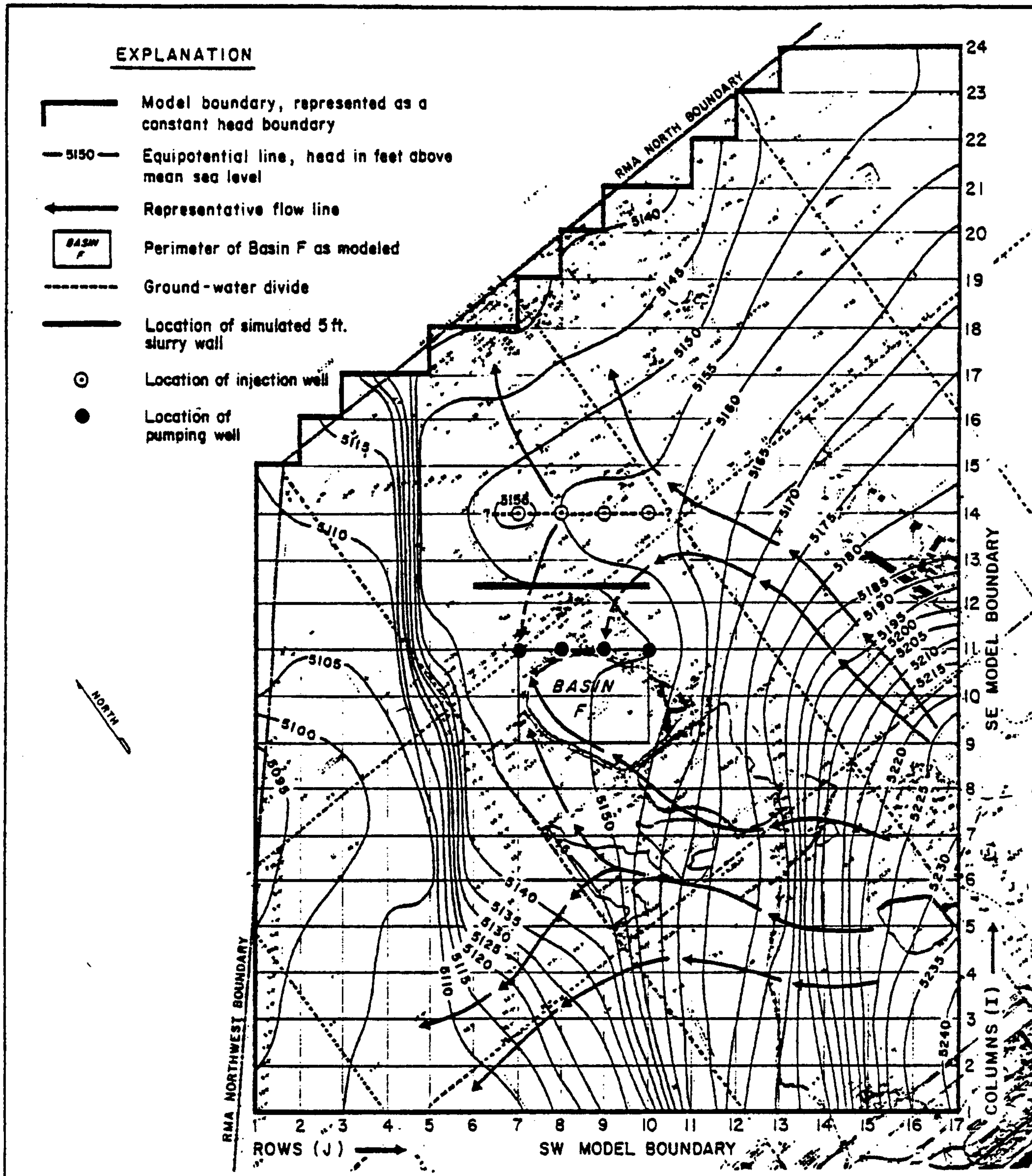
Flow changes occur locally in the area around Basin F. The four pumping wells have caused a pumping "trough" to develop, which extends somewhat further southward, compared with the previous plan.

Flow across the Arsenal and model boundaries is affected to some degree, but there is no adverse impact on the overall flow system. Flow and changes in flow resulting from this simulation are listed and compared with the calibrated run in Tables 6 and 7. Outflow across the Arsenal's north boundary is increased by approximately 13,710 gpd (4.3 percent). A reduction in outflow occurs both across the Arsenal's northwest boundary and the model's southwest boundary, amounting to 3,310 gpd (0.7 percent) and 9,653 gpd (14.4 percent), respectively. The flow into the model area across the southeast boundary is increased by about 780 gpd (0.2 percent).

7.5.3 Scheme 3 - Dewatering and Injection Wells with Bentonite Slurry Wall Near Basin F

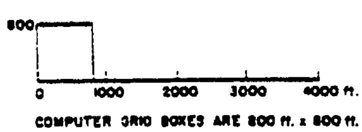
The third containment scheme involves the pumping and injection well scheme used in conjunction with a low-permeability bentonite slurry wall. The locations of the pumping and injection wells are identical to those used in the second scheme. The slurry wall is located between the well systems, north of Basin F, in a northwest-southeast orientation. The pumping wells are upgradient of the wall and the injection wells are downgradient of the wall. Total pumping and injection rates are 40 gpm, similar to those used in the first simulation of the second scheme.

The slurry wall was simulated as if it were constructed midway between columns 12 and 13, from rows 6 to 10. In order to simulate the slurry



Note

Pumping and injection rates = 10 gpm per well.



PREPARED FOR	
AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

TITLE

CONTAINMENT SCHEME 3 — SIMULATEI WATER-TABLE CONFIGURATION

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.			
COMPILED BY	MICHAEL DE CILLIS	DATE JUNE 1980	FIGURE
PREPARED BY	WILLIAM H. CICIO		17
PROJECT MANAGER	ROBERT L. STOLLAR	SCALE SHOWN	

wall, model parameters had to be adjusted. The permeability of the slurry wall is reported to be 1.5×10^{-7} cm/sec (3.2×10^{-3} gpd/sq ft) and its thickness is about 5 feet. The grid spacing of the model is 800 feet. To simulate a slurry wall about 5 feet in thickness within an aquifer width of 800 feet, the wall permeability is increased 150 times (800 is approximately 150 times larger than 5). This introduces a severe anisotropy to flow in the column direction, reducing flow from Basin F towards the Arsenal's north boundary. However, flow in the row direction would not be significantly changed because the thickness of original aquifer material available would remain essentially unchanged; that is, approximately 99 percent of the original $100 - \frac{(800 \text{ ft} - 795 \text{ ft})}{800 \text{ ft}}$. Hence, model permeabilities and transmissivities in the row direction need not be changed to simulate the slurry wall. The permeability and transmissivity values in the column direction for the nodes simulating the slurry wall were adjusted proportionately, that is, 150 times the actual permeability of the wall.

Figure 17 shows the head and flow relationships that resulted from the simulation. The overall flow regime of the modeled area has not changed significantly, however, local changes have occurred near Basin F.

The pumping "trough" created by the discharge wells is very similar to that created by the 40 gpm scheme without the slurry wall. The same is true of the rise in water levels caused by the injection wells. However, the placement of the slurry wall between the two well systems does amplify the effects. In other words, the pumping "trough" is deeper, and the rise in water levels near the injection wells is higher, a direct result of the slurry wall which reduces flow in one direction. The pumping wells do not have an unobstructed area to draw water from. Likewise, flow moving back from the injection wells towards the pumping wells is slowed by the very low permeability characteristics of the slurry wall.

The severe anisotropy imposed on the system by the slurry wall also affects boundary flows more drastically (Table 6). As the flow of the injected water toward the pumping "trough" is reduced, flow must increase elsewhere. Flow towards the Arsenal's north boundary increases by 22,650 gpd (7 percent).

The slurry wall also affects the migration of water entering the pumping "trough." As flow from the direction of the slurry wall is restricted, the required water supplying the pumping wells is derived from other areas of the aquifer. Thus, outflow across the Arsenal's northwest boundary and the model's southwest boundary is reduced, while inflow across the model's southeast boundary is increased. Changes in flow are greater than those in the same pumping scheme without the slurry wall, as shown on Table 7. The decrease in flow amounts to 5,240 gpd (1.1 percent) and 14,955 gpd (22.3 percent), from the northwest and southwest boundaries respectively, and the increased flow across the southeast boundary is 1,610 gpd (0.4 percent).

7.5.4 Scheme 4 - Additional Dewatering Wells With Bentonite Slurry Wall Near Basin F

A fourth containment scheme simulated involves, in addition to the four wells situated along the north side of Basin F, three new wells located along the northwest perimeter of Basin F. The location of these wells is shown on Figure 18. All seven wells are pumping 10 gpm for a total of 70 gpm. The 10 gpm discharge rate of each well is based on the thickness of the saturated alluvial material and the available drawdown as described previously. The treated water is being injected outside the modeled area and the impact of this injection is not simulated. The slurry wall described in the third containment scheme is included in this scheme. As shown on Figure 18, the overall flow pattern of the modeled area has not changed, but heads have been lowered in a large area around Basin F. In addition, the flow pattern around the basin has been altered.

Heads in approximately a one-square mile area around the perimeter of Basin F have dropped as much as 5 feet. Flow around Basin F is toward the pumping wells and a ground-water divide has formed to the northeast of Basin F. However, there is no distinct pumping "trough" established as was the case with the pumping and injection schemes described earlier.

Because there is no injection of treated water within the modeled area, outflow across the Arsenal's north and northwest boundaries and the model's southwest boundary decreases by approximately 25,630 gpd (7.9 percent) 13,990 gpd (2.8 percent), and 38,174 gpd (56.8 percent), respectively (Tables 6 and 7). Pumping without injection also increases the inflow

EXPLANATION

Model boundary, represented as a constant head boundary

5150 — Equipotential line, head in feet above mean sea level

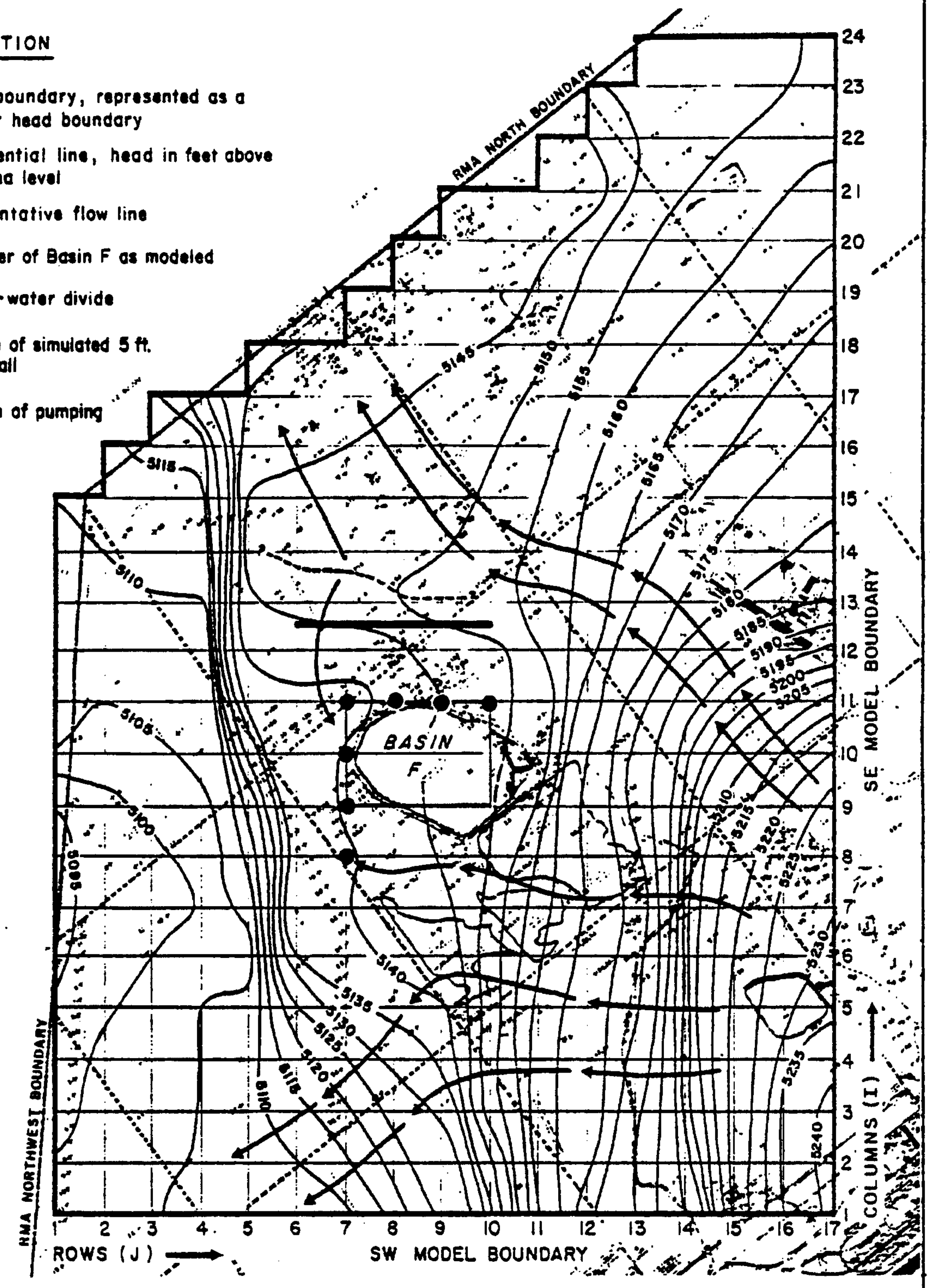
Representative flow line

Perimeter of Basin F as modeled

Ground-water divide

Location of simulated 5 ft. slurry wall

Location of pumping well



Note

Pumping rate = 10 gpm per well

800

0 1000 2000 3000 4000 ft.

COMPUTER GRID BOXES ARE 800 ft. x 800 ft.

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TITLE

CONTAINMENT SCHEME 4 — SIMULATED WATER-TABLE CONFIGURATION

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY	MICHAEL DE CILLIS	DATE JUNE 1980	FIGURE 18
	PREPARED BY	WILLIAM H. CICIO		
	PROJECT MANAGER	ROBERT L. STOLLAR	SCALE SHOWN	

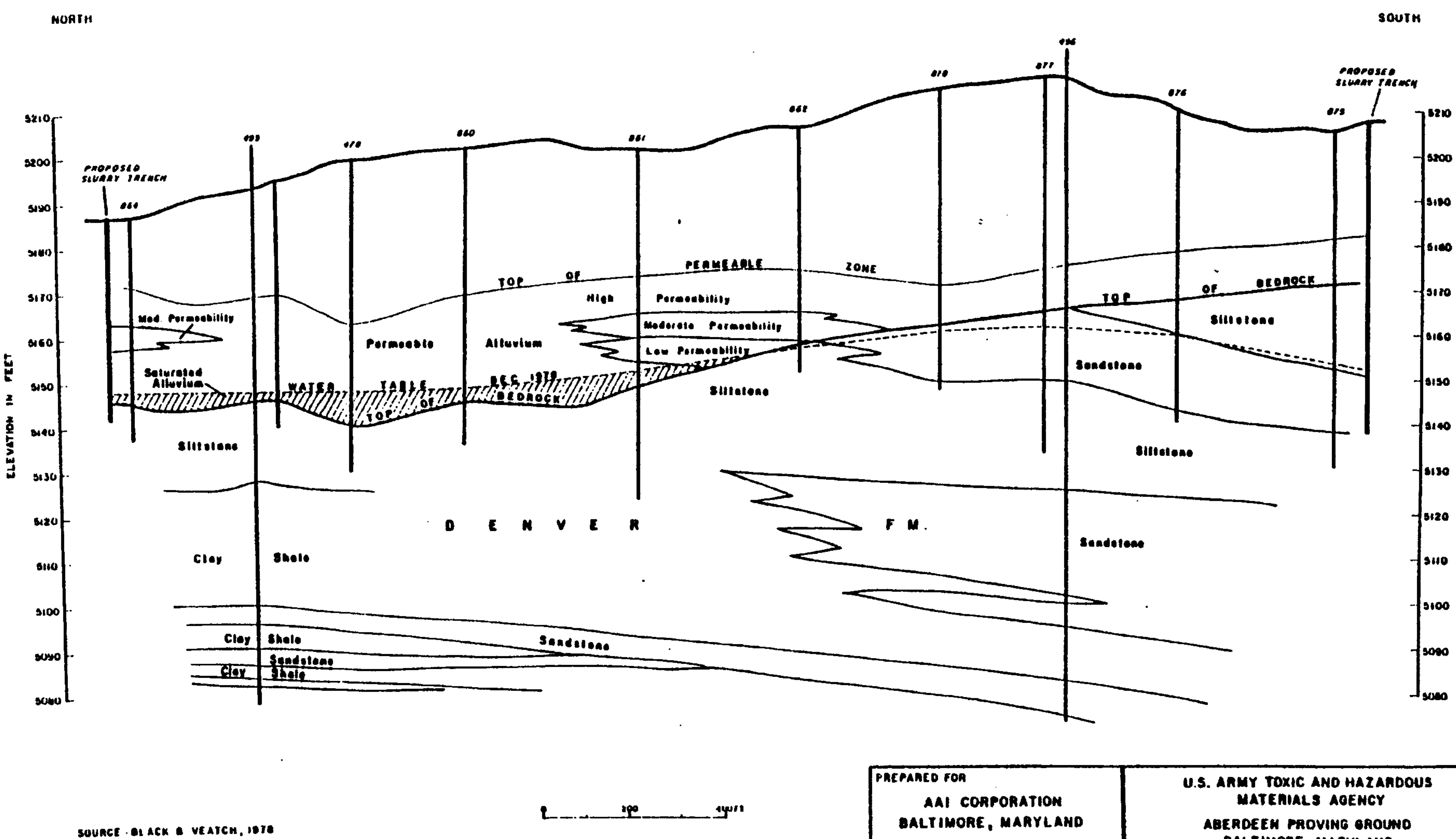
across the model's southwest boundary by about 17,640 gpd (4 percent). It is evident that this containment scheme has a more significant impact on the flow system than any of the other schemes.

7.6 Estimate of Upward Flow Into Basin F

Upward leakage of ground water from the upper artesian bedrock units into the overlying alluvial deposits (water-table aquifer), may be occurring below Basin F at the present time. Upon placement of a full-depth bentonite barrier around Basin F, dewatering may have to be initiated to control such leakage. A simple technique using Darcy's Law and a series of assumptions has been used to quantify leakage.

Hydrogeologic conditions below Basin F are complex as indicated by test wells, cross sections, and water-level information. As shown in Figure 19, which is a cross section along the eastern edge of Basin F, and believed to be typical of the entire Basin F area, the bedrock surface declines from elevation 5,170 feet in the south to elevation 5,140 feet in the north. The elevation of the water table on December 1978 was between 5,160 and 5,147 feet and was essentially unchanged in May 1979.

It can clearly be seen that the saturated alluvial material is extremely thin and reaches a maximum of 8 feet in a few places. The saturated alluvium is believed to be zero below most of the basin as indicated on the contour map (Figure 20). This map is based on numerous data points along the proposed bentonite barrier line as shown on Corps of Engineers maps and cross sections (Black and Veatch, 1978).



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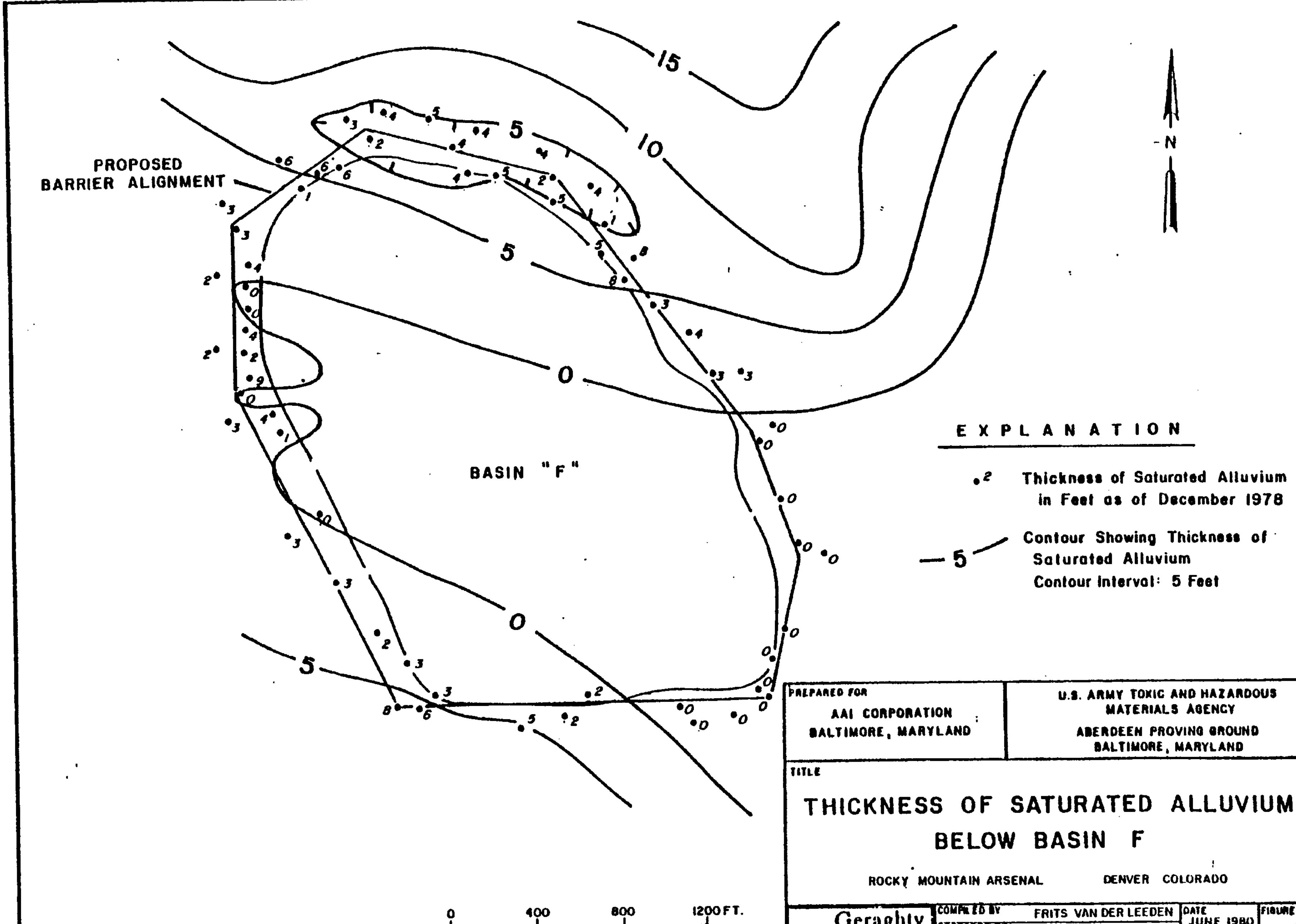
BALTIMORE, MARYLAND

TITLE

CROSS SECTION ALONG EAST SIDE OF BASIN F

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY: FRITS VAN DER LEEDEN	DATE: JUNE 1980		FIGURE 19
	PREPARED BY: CANDIE ROBERTSON			
	PROJECT MANAGER: ROBERT L STOLLAR	DWN		



SOURCE: MILLER, S.P. 1978

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TITLE

THICKNESS OF SATURATED ALLUVIUM BELOW BASIN F

ROCKY MOUNTAIN ARSENAL DENVER COLORADO

Geraghty & Miller, Inc.	COMPILED BY FRITS VAN DER LEEDEN	DATE JUNE 1980	FIGURE 20
	PREPARED BY CANDIE ROBERTSON	SCALE SHOWN	
	PROJECT MANAGER ROBERT L. STOLLAR		

Information on artesian heads below Basin F is shown on Cross Sections III and IV of this report (Plate 3). Below the northern portion of Basin F, at a shallow depth (20 feet) below the alluvium/bedrock contact, heads are at an elevation of 5,149 feet, below the central portion at 5,154 feet, and below the southern edge of the basin at 5,165 feet. These heads are respectively 2 feet, 4 feet, and 5 feet above the water-table elevation and indicate that a gradient exists for upward movement of water.

At greater depth below the alluvium/bedrock contact, the situation changes as artesian heads are several feet lower than the water-table elevation. For example, below the northern portion of Basin F, heads at a depth of 100 feet below the bedrock contact are at 5,142 feet, which is 5 feet below the water-table elevation of 5,147 feet. Below the southern part of Basin F, the artesian head of 5,155 feet is 5 feet below the 5,160 feet water-table elevation. This zone of deeper ground-water flow is not further considered in the calculation.

The confining bed is a clay shale and a thickness of 20 feet has been assigned to this unit to reflect flow conditions in the upper bedrock zone. A vertical permeability of 0.1 gpd/sq ft (equivalent to 4.7 x $^{-6}$ cm/sec), is believed to be representative of the confining zone. No actual vertical permeabilities are available from the bedrock in the Basin F area. In actuality, conditions below Basin F may be far more complex. Some of the sandstone beds may be in direct contact with the alluvium (as shown on the cross section). Such a situation would, of course, increase the vertical permeability as the true confining bed is missing.

The area of the Basin F area was planimetered and estimated at 3,500,000 square feet. In addition, the following assumptions were made in the leakage calculation:

a) Head differential (Δh) = 4 feet average across the entire Basin F.

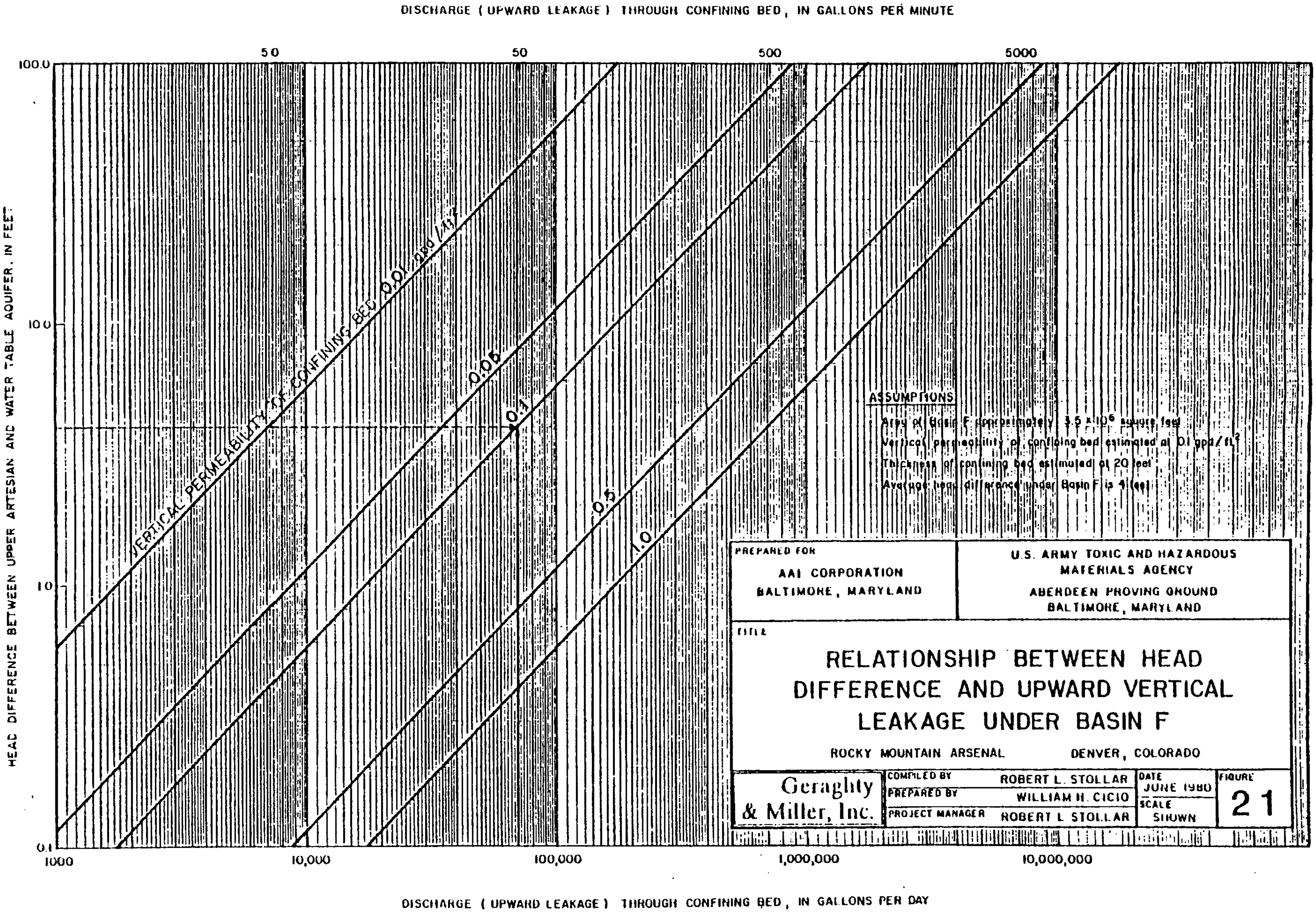
b) Vertical permeability = 0.1 gpd/sq ft.

c) Confining bed thickness = 20 feet.

The 4-foot head differential produces a discharge (upward leakage) through the confining bed of 0.02 gpd/sq ft. Upward leakage below the entire Basin F area is then 70,000 gpd or about 50 gpm.

The above calculation assumes pumping the 50 gpm to maintain a constant water-table altitude but does not consider lowering of the water table due to dewatering. Because of the thin saturated alluvium below Basin F, dewatering is difficult and impractical. At the most, water levels might be lowered a few feet below the northern part of the basin where wells could be screened in the alluvium. However, assuming an additional 2 feet of water-table decline over the entire basin area, the head differential (Δh) would increase from 4 to 6 feet or 50 percent. As the relationship between discharge and Δh is linear, the discharge or upward leakage would also increase 50 percent to 100,000 gpd or 70 gpm.

It should be noted that these leakage calculations do not reflect changes in artesian head below Basin F which may be expected to occur when a full barrier is in place. For convenience, Figure 21 shows the relationship of upward vertical flow for various head differentials and vertical pemeabilities of the confining layer.



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RELATIONSHIP BETWEEN HEAD DIFFERENCE AND UPWARD VERTICAL LEAKAGE UNDER BASIN F

ROCKY MOUNTAIN ARSENAL DENVER, COLORADO

Geraghty & Miller, Inc.

COMPILED BY	ROBERT L. STOLLAR	DATE JUNE 1980	FIGURE 21
PREPARED BY	WILLIAM H. CICIO	SCALE SHOWN	
PROJECT MANAGER	ROBERT L. STOLLAR		

8.0 CONCLUSIONS

1. The RMA is located in the Denver Basin, a geologic structural depression filled with a series of sandstones and shales totaling 15,000 feet in thickness.

2. Ground water is obtained from alluvial deposits and bedrock aquifers. Principal bedrock aquifers, from land surface down, are the Denver, Arapahoe, Laramie, Fox Hills, Dakota, and Fountain-Lyons Formations.

3. The alluvial deposits laid down in ancient erosional valleys have a maximum thickness of about 140 feet on the Arsenal and extend into the South Platte River Valley. Where sufficiently thick and saturated, this aquifer is capable of yielding large supplies of water.

4. The Denver Formation crops out at the land surface. It consists of carbonaceous shales and claystones with occasional sandstone and siltstone lenses. These lenses range in thickness from a few feet to 20 feet and occupy sinuous channels that are difficult to trace but in some areas extend for at least 3,000 feet.

5. The Denver Formation is separated from the underlying Arapahoe Formation by a clay/shale buffer zone, 75 to 200 feet thick.

6. The Arapahoe Formation is the most important aquifer in the Denver area. It yields good quality water and is tapped by some 6,000 stock, domestic, and municipal wells.

7. Depth to the Arapahoe aquifer below the RMA land surface varies

from 700 feet along the south boundary to 300 feet along the north boundary.

8. Recharge to the ground-water system is from precipitation on the outcrop area, infiltration of surface water, and vertical leakage from confining beds. Total recharge to the Arapahoe-Denver sequence in the Denver Basin is estimated at 100 mgd.

9. Pumpage from the Arapahoe-Denver aquifers approaches 150 mgd and is in excess of recharge. Ground water is being taken from storage within the aquifers and this withdrawal has resulted in a 100 to 200 feet water-level decline in the Denver area.

10. Regional ground-water flow is from south to north in the deep artesian aquifers. This flow pattern has been modified by pumpage in the Denver region. The potentiometric surface of the Arapahoe aquifer below the RMA in 1978 was at an elevation of 5,000 to 5,100 feet above msl.

11. Water-table elevations range from 5,300 feet in the southeast corner of the RMA to 5,100 feet along the northern boundary. Regional flow is northward toward the South Platte River Valley. Excluding local anomalies, the regional water-table flow pattern found during this 1980 study is identical to that of 1956.

12. The quality of ground water in the vicinity of the Arsenal varies considerably. Water in the alluvial aquifer along the South Platte River is mineralized and unsuitable for domestic and municipal supplies. As irrigation water it is of salinity-hazard classification. Water in the bed-

rock aquifers is less minealized and of fair to good quality.

13. To study hydrogeologic conditions below the Arsenal, 11 cross sections were prepared. Soil descriptions were converted to relative permeabilities and correlated. The sections show field and laboratory permeabilities, screen settings, potentiometric levels, water-table elevations, and equipotential lines.

14. The cross sections reveal no uniform permeability contrast between the alluvium and the bedrock. In some areas, zones of high and moderate permeability extend from the alluvium into the Denver Formation.

15. Ground-water flow occurs in both alluvium and bedrock aquifers and is part of one continuous hydrologic system as indicated by mapping of equipotential lines. Generally speaking, the amount of ground-water flow in the bedrock aquifer is small compared to that in the alluvium.

16. Contours on the water table show the existence of a 30-foot high mound below the South Plants. This mound is due to leakage of water from pipes into low-permeability material.

17. This man-made anomaly of the water table presently is a major driving force of the ground-water flow system on the Arsenal. Flow lines from the mound radiate in all directions and the head differential between the mound and the northwest boundary is 145 feet, equivalent to a high gradient of about 0.01 ft/ft.

18. Equipotential lines indicate a vertical component of ground-water

throughout the Arsenal and water from the alluvium can migrate to deeper formations. Vertical flow has been identified in the South Plants and Basin A Neck areas.

19. The configuration and movement of contaminant plumes are in accordance with the equipotential lines and limiting flow lines. Water from Basins A and F will continue to flow toward the north boundary. Flow originating at the mound in the South Plants area will continue to move toward the northwest boundary.

20. A flow-net analysis and quantification of ground-water flow cannot be made because of complicated hydrogeololgy, unequal distribution of well data, and contradictory field permeability values from pumping, slug, and falling-head tests.

21. Numerous actual and potential sources of ground-water contamination exist on the Arsenal. Toxic chemical wastes have been stored and disposed of in pits, basins, lagoons, sewer systems, and building drains; leaks and spills have occurred. Prime sources of contaminants are the South Plants area and Basin A. Secondary sources of contamination are Basin F and the sanitary sewer and industrial waste lines.

22. The sanitary sewerage system, when tested by Black and Veatch in 1979, was found to be in poor condition in many places and subject to infiltration and exfiltration. A newly-prepared cross section along the sewer line shows that the line was below the water table in May 1979 in the Basin A area. It is likely that a similar situation existed in the 1942-52

period when Basin A was used as a liquid disposal area. The widespread presence of Nemagon in the line in 1979 tends to support the infiltration hypothesis.

23. A comparison of the location of the sanitary sewer lines and iso-concentration maps of the four selected contaminants shows no clear-cut correlation between the lines and high concentrations of contaminants. Possible exceptions are high (above 500 ug/l) DCPD levels below the sanitary line at the South Plants and below exposed sewer pipe in Basin A.

24. The contaminated industrial waste line was losing fluid at the rate of 20,000 gpd between the South Plants and Basin F when surveyed in June 1960. A newly prepared cross section of the industrial waste sewer shows that in May 1979 the water table was above the line over a distance of 2,000 feet north of the Shell plant in the Basin A area thus presenting favorable conditions for infiltration of ground water.

25. A comparison of the location of the contaminated waste line with isoconcentration maps of the four selected contaminants shows no clear correlation between chemical concentrations and the waste line location.

26. In order to interpret water-quality conditions in the subsurface and map lateral and vertical migration of chemical constituents, concentrations of four water-quality parameters, chloride, DIMP, DCPD, and DBCP (Nemagon) were plotted and contoured on maps and cross sections.

27. The chloride plume is larger than any other contaminant plume. Major concentrations of 5,000 mg/l are centered in the Basins A and F

areas. At the South Plants, where concentrations are lower, a chloride plume is discharging into Ladora Lake.

28. High chloride concentrations of 2,000 mg/l originating adjacent to Basin F could be indicative of a leak or leaks in the Basin F liner. The chloride plume extends a considerable distance across the north boundary but concentrations of 1,000 mg/l do not extend further than 0.5 mile across the RMA property line. Off-post chloride levels at the northwest boundary are lower than in previous years.

29. Chloride levels confirm vertical migration of ground water below the Basin A Neck area. At a depth of 200 feet, chloride concentrations are 6,300 mg/l. In one well cluster near Basin F, chloride values are 110 mg/l at a depth of 200 feet, 150 mg/l at 150 feet, and 610 mg/l at the water table.

30. High DIMP concentrations (10,000 to 20,000 ug/l) occur near presumed source areas in Basins A, C, and F. The DIMP plume extends across the entire central part of the Arsenal and moves to the northwest and north boundaries. Concentrations in off-post wells, 0.5 mile north of the boundary, are 1,000 ug/l.

31. Vertical migration of DIMP is evident below the Basin A Neck area with concentrations of 1,900 ug/l occurring at a depth of 200 feet.

32. Major concentrations of DCPD (2,000 to 15,000 ug/l) occur in the South Plants area on the ground-water mound. Another DCPD plume originates in the Basin A area. Two DCPD plumes originate along Basin F and could

signify leakage from a ruptured liner in Basin F. The DCPD plume extends across the north boundary for 0.5 mile.

33. Vertical migration of DCPD is evident in the South Plants area where DCPD is found 30 feet below the top of the water table.

34. The major area of Nemagon contamination (30,000 ug/l) occurs in the South Plants area adjacent to Building 451 in the center of the ground-water mound. A Nemagon plume is migrating toward the Basin A area. Another Nemagon plume occurs south of Basin C and is moving toward the northwest boundary. A third plume originates along the eastern boundary of Basin F and might originate from Basin F or sewer leakage. The Nemagon plume in low concentrations (4 ug/l) extends 1.5 miles across the north boundary.

35. Vertical movement of Nemagon in ground water has occurred in the South Plants area where a 7.7 ug/l Nemagon value has been found 80 feet below the water table (100 feet below land surface).

36. Contaminant migration will continue in western, northern, and eastern directions from the ground-water mound and the principal contaminant source in the South Plants area.

37. Vertical migration of polluted ground water through abandoned farm wells on RMA is a possibility. Eight former farm wells tapping the Arapahoe aquifer are located within the chloride, DIMP, DCPD, and Nemagon plumes. It may be possible to locate these wells and plug and seal them.

38. The quality of existing subsurface and water-quality data is good

but mainly pertains to the alluvial formation. Little information is available on the Denver Formation and on water-level changes with depth. Field permeability tests do not correlate with pumping test data. These data gaps make it impossible to determine the lower boundary of the flow system.

39. The geographical distribution of the data points is uneven, with large areas of the Arsenal virtually untested.

40. The sheer volume of data generated at the RMA at the present time makes study and interpretation of data extremely costly and difficult. Interpretation and simplification of the data collection and monitoring program is proposed to establish a basic, manageable program.

41. Conclusive information to solve site-specific problems including Basin F, the sanitary and waste sewer lines, flow and transport of contaminants in First Creek and irrigation laterals, the situation at the lakes, and the possible impact of contaminated ground water on the Arapahoe Formation from abandoned farm wells is not available.

42. Work plans are submitted for an Arsenal-wide survey of contaminant migration, (a) at the northwest boundary, (b) at the South Plants and southern portion of the Arsenal, (c) at the eastern portion of the Arsenal, and (d) in the Basin A Neck area.

43. A program should be developed to determine whether Basin F is leaking as present water-level data are insufficient. Test drilling adjacent to the basin will be required.

44. Presently a number of ground-water monitoring programs are being carried out for a variety of objectives. Ground-water monitoring should be integrated and reduced to arrive at a more manageable and cost-effective program. This can be achieved by incorporating new Arsenal-wide objectives, proper well selection, establishing contaminant criteria, and sampling protocol.

45. Four Basin F containment schemes were simulated with a digital computer model to determine their impact on the ground-water flow system. Contaminant migration was not modeled.

46. Scheme 1 was a full-depth impermeable bentonite clay barrier completely surrounding Basin F. It was assumed that the barrier was anchored in the first low-permeability bedrock formation. Outflow across the Arsenal's north boundary increased by about one percent and decreased by less than one percent across the northwest boundary.

47. Scheme 2 consisted of dewatering wells placed along the northern margin of Basin F to form a dewatering trough. Intercepted contaminated ground water would be treated to remove contamination, and reinjected downstream of the trough. Ground-water flow systems were simulated at two pumpage rates. In the first case, the amount pumped and reinjected was 40 gpm, resulting in increased flow of 3.5 percent across the north boundary and decreased flow of less than one percent across the northwest boundary. When capturing all ground-water underflow in this area, about 52 gpm, and reinjecting this amount as above, the system experienced increased flow of 4.5 percent along the north boundary and decreased flow of less than one

percent along the northwest boundary.

48. Scheme 3 consisted of placing a low-permeability bentonite slurry wall to the north of Basin F, and operating dewatering wells on the upgradient side of the wall, with subsequent treatment and reinjection on the downgradient side of the wall. A total of 40 gpm was pumped and injected. Flow across the north boundary increased by 7 percent and decreased by about one percent across the northwest boundary.

49. Scheme 4 consisted of placing a low-permeability bentonite slurry wall to the north of Basin F and operating dewatering wells upgradient of the wall and along the west side of Basin F. The wells pumped a total of 70 gpm. Reinjection of the water took place outside the modeled area. Outflow across the Arsenal's north and northwest boundaries was reduced by about 8 and 3 percent, respectively.

50. Upon placement of a full-depth bentonite barrier around Basin F, it is expected that upward leakage from the artesian zones (bedrock) to the water-table zone (alluvium) will occur. Heads are 4 feet higher in the artesian zone than the water-table zone and the leakage rate is estimated at 70,000 gpd or approximately 50 gpm. Dewatering operations may have to be initiated to control this leakage.

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10.0 GLOSSARY

Aquifer - A geologic formation, group of formations, or part of a formation that is capable of yielding a significant amount of water to a well or spring.

Artesian - The occurrence of ground water under greater than atmospheric pressure.

Artesian (Confined) Aquifer - An aquifer bounded by beds of low permeability containing water under greater than atmospheric pressure.

Barrier Boundary - An aquifer system boundary equivalent to a rock mass that is not a source of water.

Bentonite - A clay formed from a decomposition of volcanic ash with great ability to absorb or adsorb water but of very low permeability.

Carbonate Rock - A rock primarily composed of $CaCO_3$, such as limestone or dolomite.

Casing - Steel or plastic pipe or tubing that is welded, screwed, fitted, or glued together and lowered into a borehole to prevent entry of loose rock, gas, or liquid or to prevent loss of drilling fluid into porous, cavernous, or fractured strata.

Cone of Depression - The depression, approximately conical in shape, that is formed in a water-table or potentiometric surface when water is removed from an aquifer.

Consumptive Use - That part of the water withdrawn that is no longer available to the system because it has been either evaporated, transpired, incorporated into products and crops, or otherwise removed from the immediate water environment.

Contamination - The degradation of natural water quality as a result of man's activities, to the extent that its usefulness is impaired. There is no implication of any specific limits, since the degree of permissible contamination depends upon the intended end use, or uses, of the water.

Crystalline Rock - Rock consisting of minerals in a crystalline state such as igneous and metamorphic rocks.

DBCP - 1,2-dibromo, 3-chloropropane (Nemagon).

DCPD - Dicyclopentadiene.

Digital Computer Model - A model of an aquifer system in which ground-water flow is described by numerical equations with specified values for boundary conditions, aquifer geometry and parameters, and aquifer stesses, which are solved on a digital computer.

DIMP - Diisopropylmethylphosphonate.

Electric Log - The log of a well obtained by lowering electrodes in the hole and measuring various electrical properties of the geological formations traversed.

Equipotential Line (Surface) - A line (surface) in a three-dimensional ground-water flow field such that the total hydraulic head is the same everywhere on the line (surface).

Exfiltration - The leakage of effluent from sewage pipes into the surrounding soils.

Flow Net - The set of intersecting equipotential lines and flow lines representing two-dimensional steady flow through a porous media.

Flow Path - The direction of movement of ground water and any contaminants that may be contained therein, as governed principally by the hydraulic gradient.

Fracture - A break in a rock formation due to structural stresses. Fractures may occur as faults, shears, joints, and planes of fracture cleavage.

Ground Water - Water beneath the land surface in the saturated zone that is under atmospheric or artesian pressure. The water that enters wells and issues from springs.

Ground-Water Divide - An imaginary impermeable boundary through which no flow takes place. Flow on either side of this boundary is usually in opposing directions.

Ground-Water Reservoir - The earth materials and the intervening open spaces that contain ground water.

Hazardous Waste - Any waste or combination of wastes which pose a substantial present or potential hazard to human health or living organisms.

Head - The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.

Hydraulic Conductivity - The quantity of water that will flow through a unit cross-sectional area of a porous material per unit of time under a hydraulic gradient of one at a specified temperature.

Hydraulic Gradient - The change in static head per unit of distance along a flow path.

Infiltration - Seepage of water from ground surface or the unsaturated zone into the saturated zone or leakage of effluent from surrounding soils or ground-water system into sewer pipes.

Injection Well - A well used for injecting fluids into an underground stratum.

Intermittent Stream - A stream which flows only during a portion of the year.

Irrigation Return Flow - Irrigation water which is not consumed in evaporation or plant growth, and which returns to a surface stream or ground-water reservoir.

Leachate - The liquid that has percolated through solid waste or other man-emplaced media from which soluble components have been removed.

Lenticular - A mass of rock that thins out from the center to a thin edge all around.

Limiting Flow Line - A flow line separating two major components of flow direction.

Monitoring (Observation) Well - A well used to measure ground-water levels, and in some cases, to obtain water samples for water-quality analysis.

Nemagon - Trade name for DBCP.

Organic - Being, containing, or relating to carbon compounds, especially in which hydrogen is attached to carbon, whether derived from living organisms or not; usually distinguished from inorganic or mineral.

Permeability - A measure of the capacity of a porous medium to transport fluid (see Hydraulic Conductivity).

Plume - A body of contaminated ground water originating from a specific source and influenced by such factors as the local ground-water flow pattern, density of contaminants, and character of the aquifer.

Potentiometric Surface - The surface defined by the levels to which ground water will rise in tightly cased wells that tap an artesian aquifer.

Public Water Supply - A system in which there is a pureyor and customers; the purveyor may be a private company, a municipality, or other governmental agency.

Recharge - The addition of water to the ground-water system by natural or artificial processes.

Recharge Boundary - An aquifer system boundary that adds water to the aquifer, e.g. streams or lakes.

Regional Underflow - The amount of ground-water movement through an aquifer.

Runoff - Direct or overland runoff is that portion of rainfall which is not absorbed by soil, evaporated or transpired by plants, but finds its way into streams as surface flow. That portion which is absorbed by soil and later discharged to surface streams is ground-water runoff.

SAR (Sodium Adsorption Ratio) - A ratio of sodium to calcium and magnesium used to express the sodium content of water as a guide to suitability for irrigation.

Saturated Zone - The zone in which interconnected interstices are saturated with water under pressure equal to or greater than atmospheric.

Sedimentary Rocks - Rocks formed of sediment, such as sandstone, shale, or limestone.

Sinuous - Characterized by many curves or turns.

Steady-State Flow - The flow that occurs when, at any point in a flow field, the magnitude and direction of the discharge are constant in time.

Storage (Aquifer) - The volume of water held in the interstices of the rock.

Surface Water - That portion of water that appears on the land surface, i.e., oceans, lakes, rivers.

TDS (Total Dissolved Solids) - A value, usually in mg/l, of the total amount of solid residue remaining upon the evaporation of clear water (filtered with 0.45-micron pore-size filter).

Toxicity - The ability of a material to produce injury or disease upon exposure, ingestion, inhalation or assimilation by a living organism.

Transient Flow - The flow that occurs when, at any point in a flow field, the magnitude and direction of the discharge changes with time.

Transmissivity - The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unsaturated Zone (Zone of Aeration) - Consists of interstices occupied partially by water and partially by air, and is limited above by the land surface and below by the water table.

Valley-Fill Aquifer - A saturated deposit in a valley consisting of unconsolidated rock waste derived from erosion of bordering mountains.

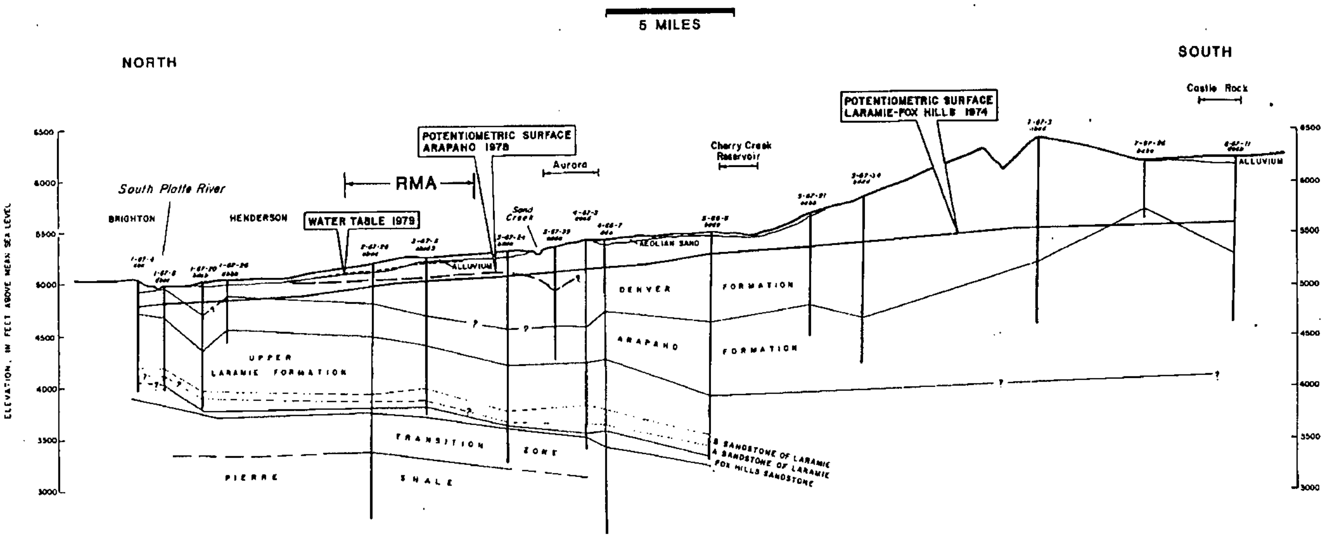
Water Table - That surface in an unconfined ground-water body at which the pressure is atmospheric. It defines the top of the saturated zone.

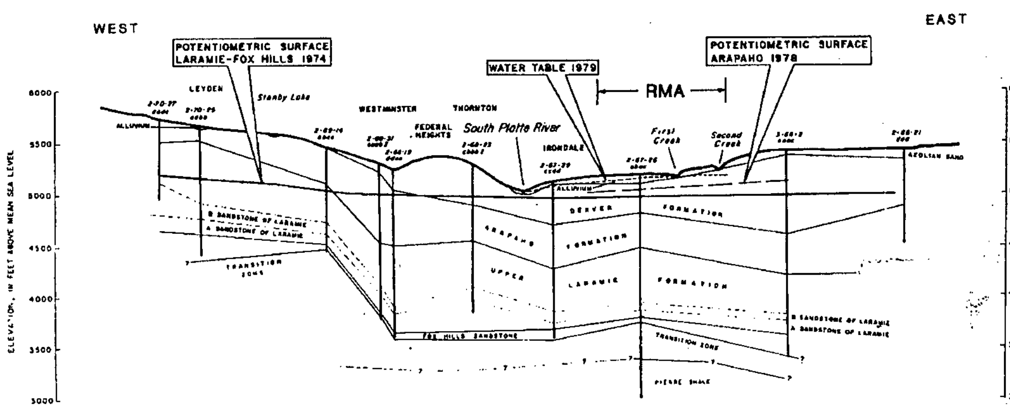
Water-Table Aquifer - An aquifer containing water under atmospheric conditions.

Well - An artificial excavation that derives fluid from the interstices of the rocks or soils which it penetrates, except that the term is not applied to ditches or tunnels that lead ground water to the surface by gravity. With respect to the method of construction, wells may be divided into dug wells, bored wells, drilled wells, and driven wells.

Well Screen - A perforated section of well casing or specially fabricated material placed opposite a water-bearing zone.

Withdrawal - The volume of water pumped from a well or wells.





EXPLANATION

------------ Elevation of water table at RMA, May 1979

— — — — Potentiometric surface of Arapaho Formation, 1978

———— Potentiometric surface of Laramie-Fox Hills aquifer, 1974

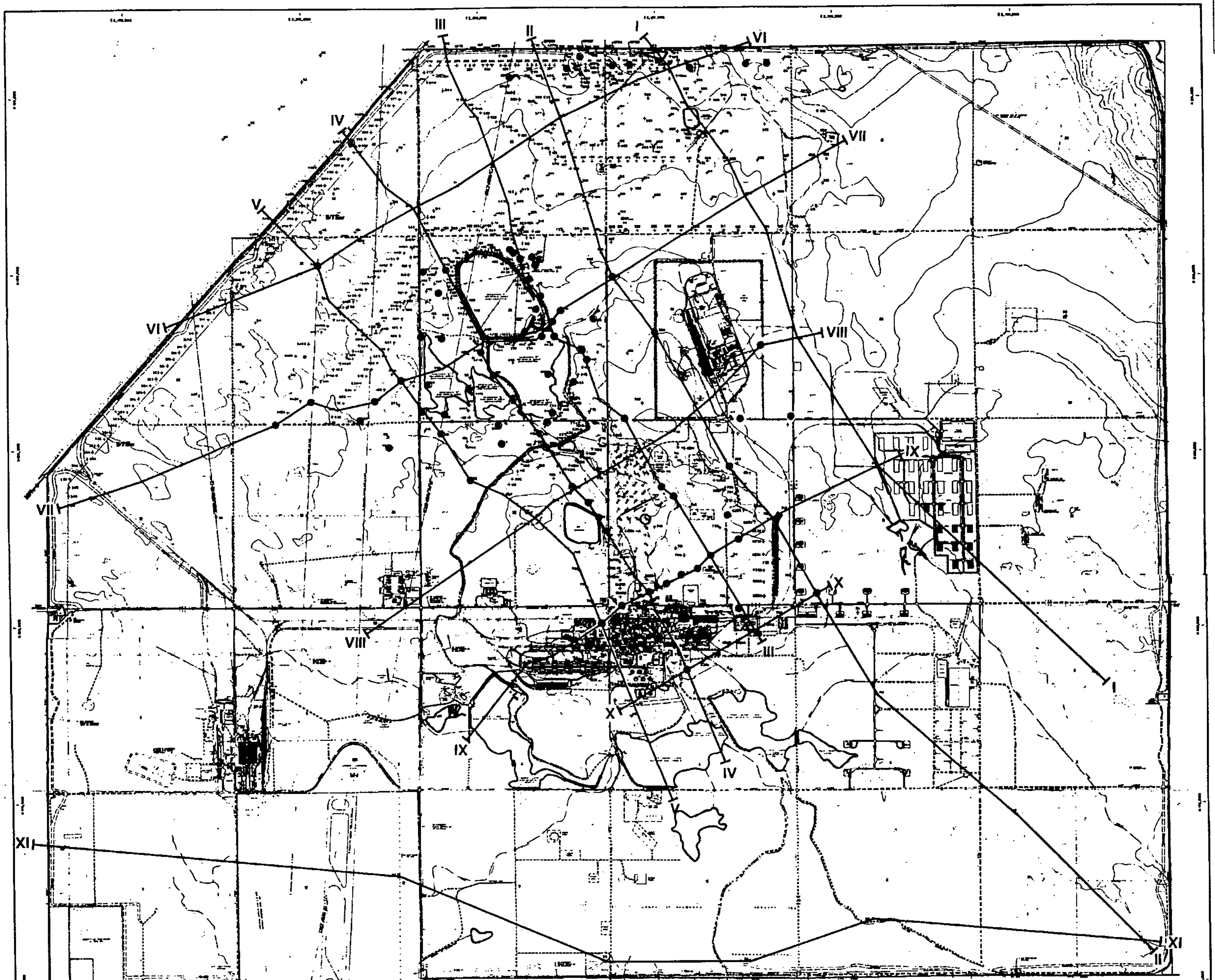
VERTICAL EXAGGERATION : 20x

AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

REGIONAL GEOLOGIC CROSS SECTIONS THROUGH THE DENVER BASIN

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Daniel A. Nochman	March, 1980	PLATE 1
	William H. Cicle	Shown	
	Robert L. Stollar		



EXPLANATION

● Well Depth Greater Than 75 ft.

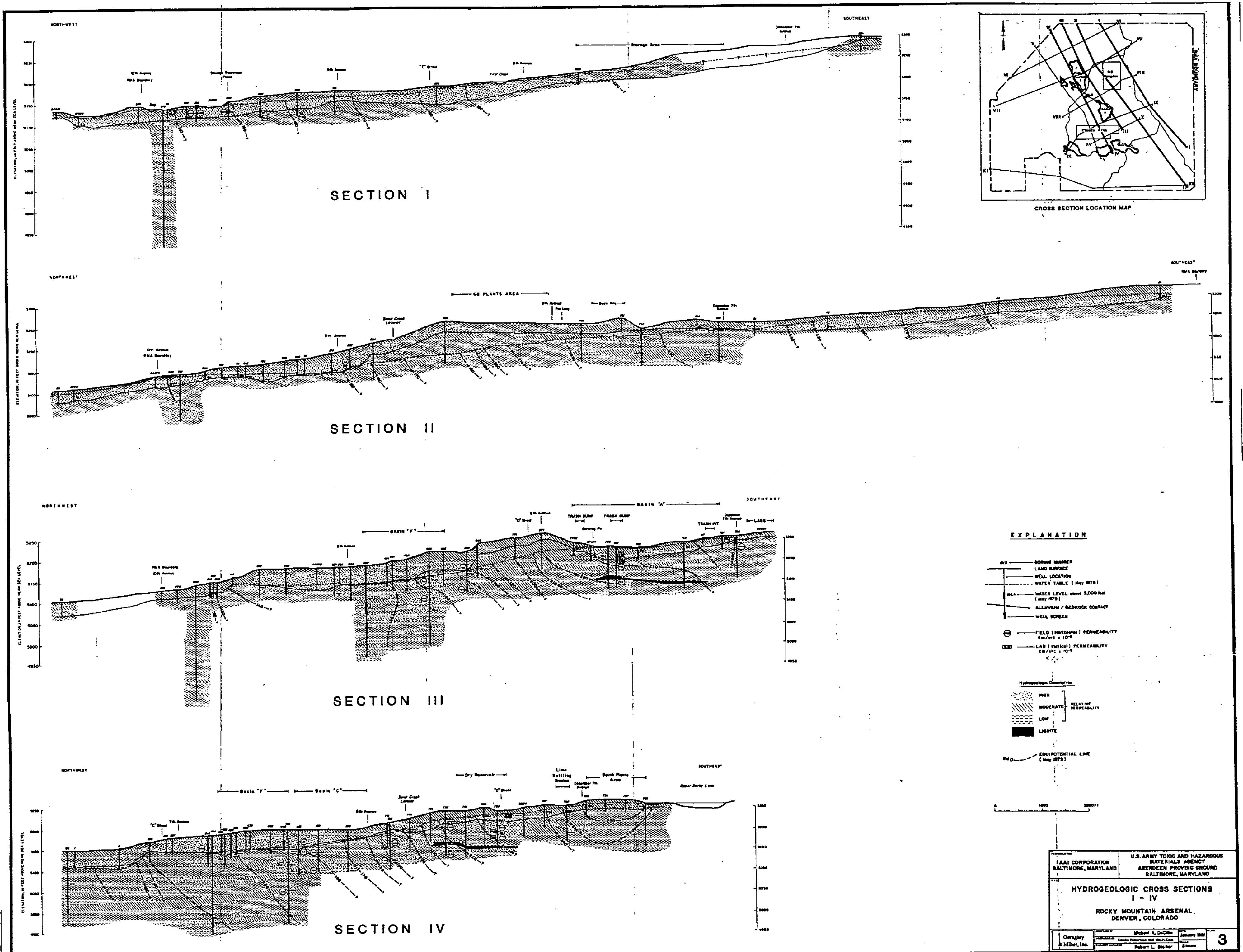
Line of Section

AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

LOCATION OF CROSS SECTIONS

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeCillis Candis Emerson and Wm. H. Coe Robert L. Stollar	January 1981 Shown	2



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ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

HYDROGEOLOGIC CROSS SECTIONS I – IV

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

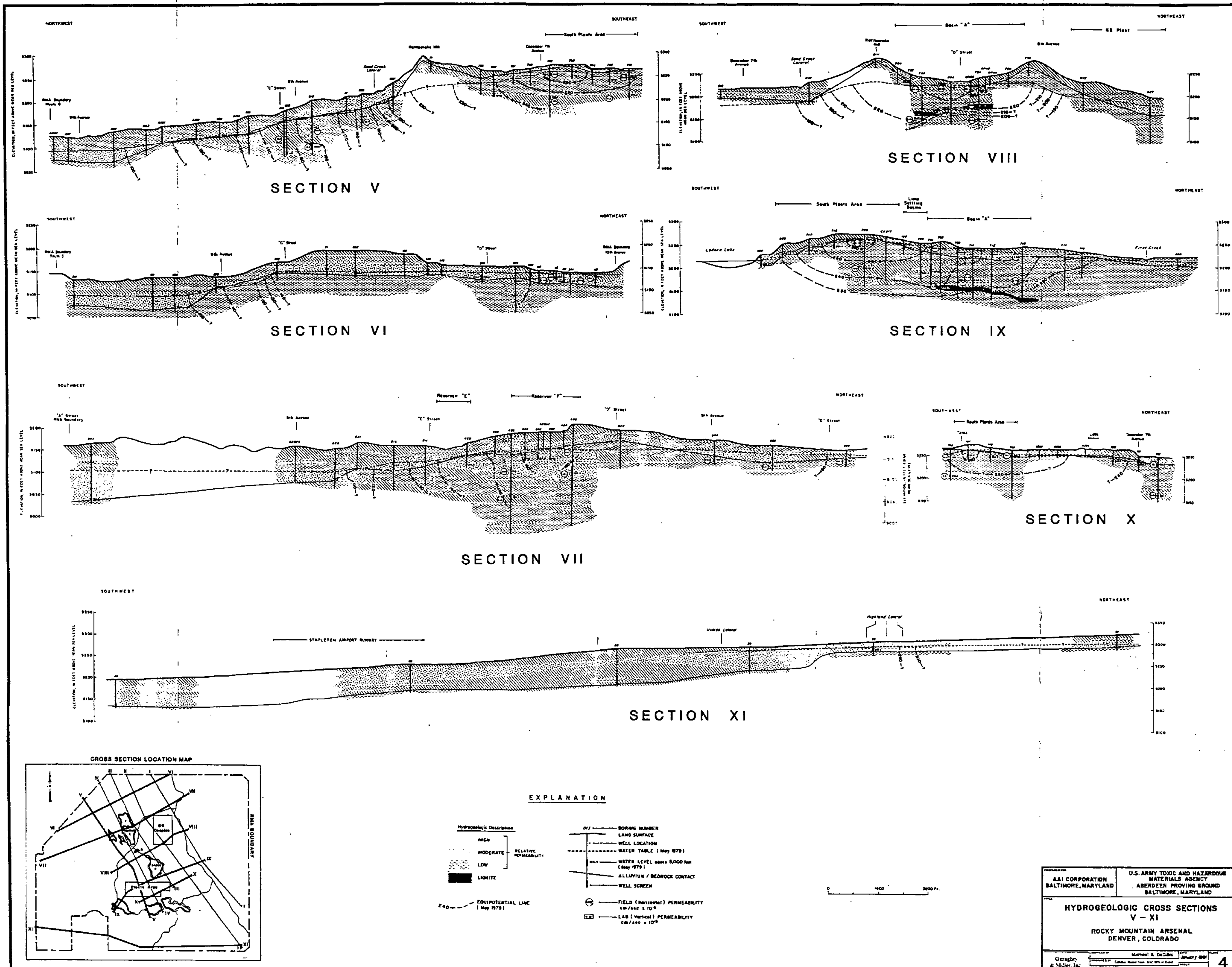
Geraghty & Miller, Inc.

Michael A. DeCillis

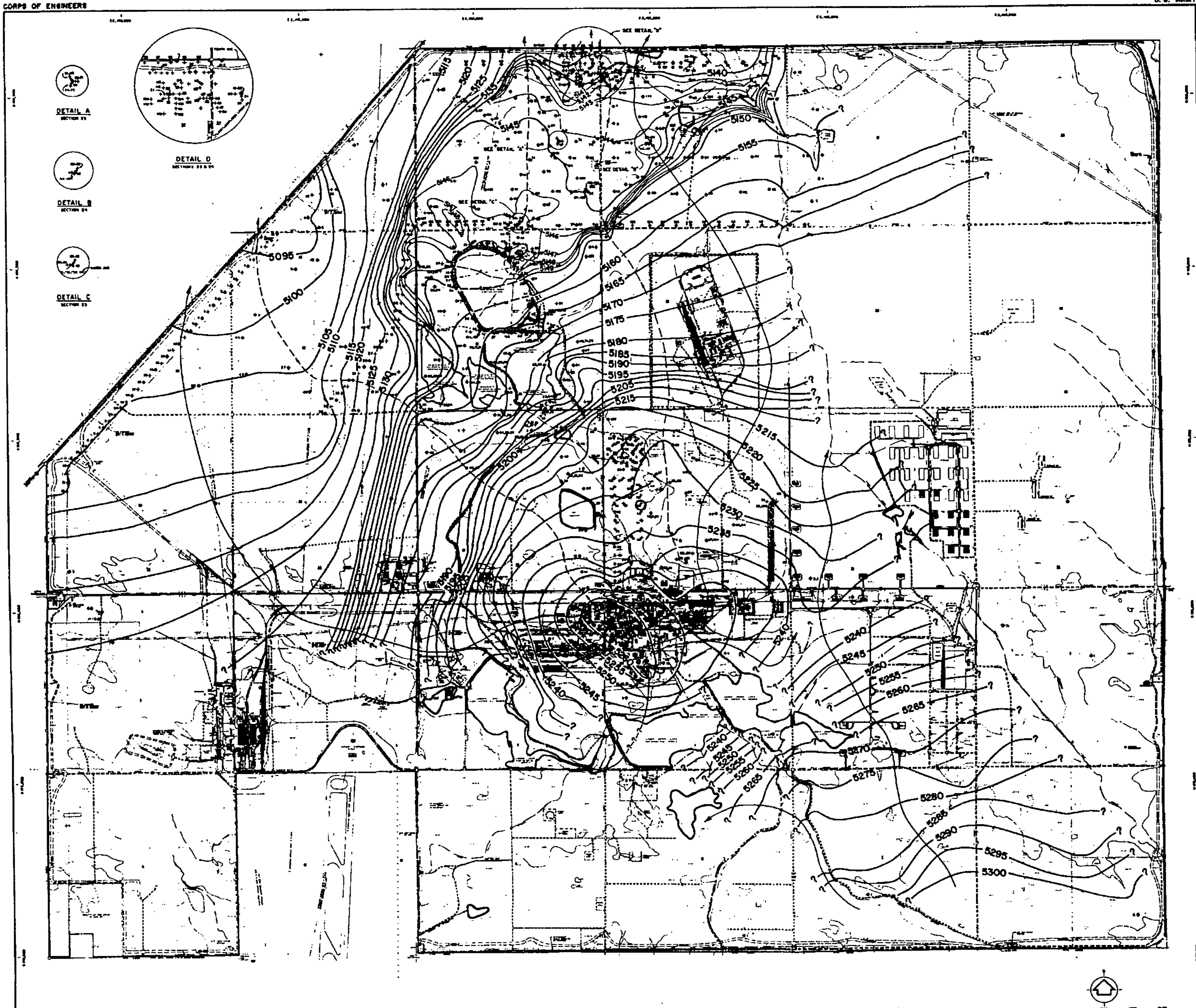
Robert L. Stoller

January 1982

3



SECTION V
SECTION VI
SECTION VII
SECTION VIII
SECTION IX
SECTION X
SECTION XI
NORTHWEST
SOUTHEAST
SOUTHWEST
NORTHEAST
South Plants Area
Basin "A"
STAPLETON AIRPORT RUNWAY
CROSS SECTION LOCATION MAP
RMA BOUNDARY
EXPLANATION
Hydrogeologic Description
HIGH
MODERATE
LOW
LIGNITE
RELATIVE PERMEABILITY
EQUIPOTENTIAL LINE (May 1979)
BORING NUMBER
LAND SURFACE
WELL LOCATION
WATER TABLE (May 1979)
WATER LEVEL above 5,000 feet (May 1979)
ALLUVIUM / BEDROCK CONTACT
WELL SCREEN
FIELD (Horizontal) PERMEABILITY cm/sec x 10⁻⁶
LAB (Vertical) PERMEABILITY cm/sec x 10⁻⁶
0
1600
3200 Ft.
AAI CORPORATION
BALTIMORE, MARYLAND
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND
HYDROGEOLOGIC CROSS SECTIONS
V – XI
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO
Geraghty & Miller, Inc.
Michael A. DeCillis
January 1981
Robert L. Stollar
4



EXPLANATION

—5155— Water-Level Elevation in feet above mean sea level

Limiting Flow Line

Representative Flow Line

Ground-Water Divide

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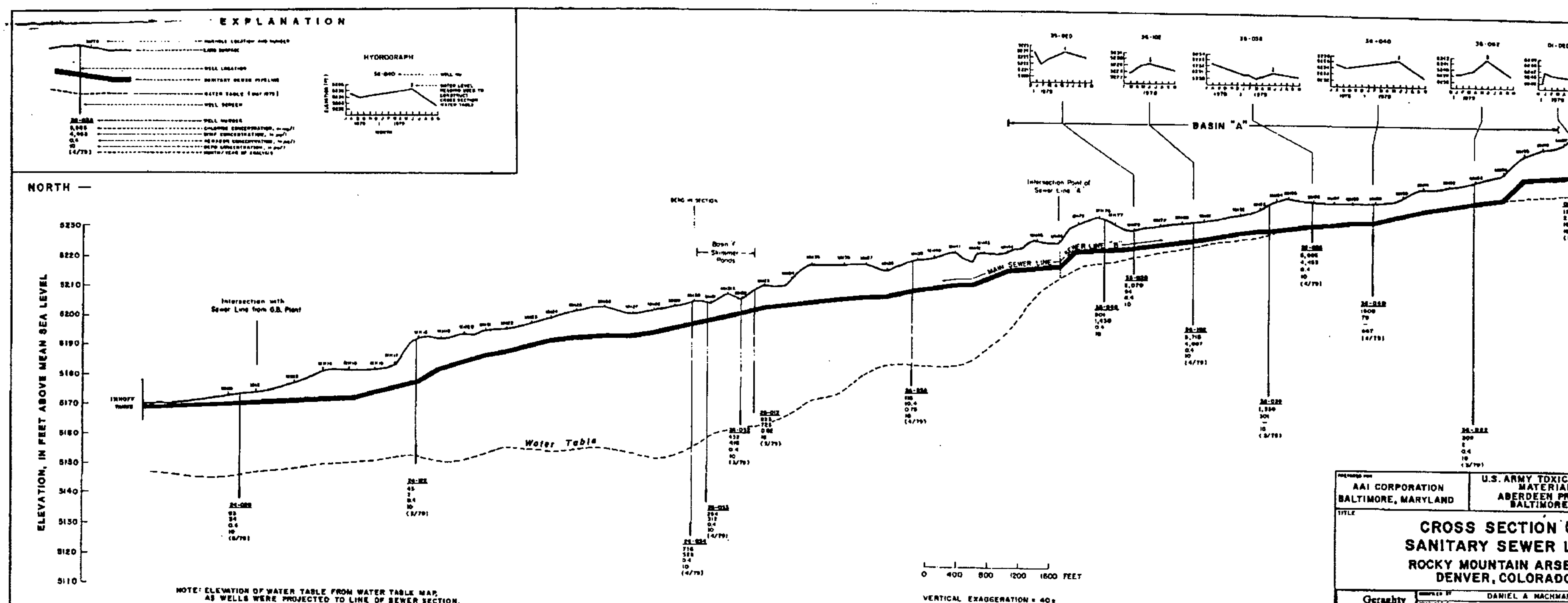
ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

CONFIGURATION OF THE WATER TABLE
MAY 1979

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeCillis	January 1981	5
	Candis Robertson and Wm H Cole	Shown	
	Robert L. Stollar		



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ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

CROSS SECTION OF SANITARY SEWER LINE

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.

DANIEL A. NACHMAN
WILLIAM H. CICIO
ROBERT L. STOLLAR

MAR. 1980
SHOWN
PLATE 6

007028-00 (6)
BB100054 (6)

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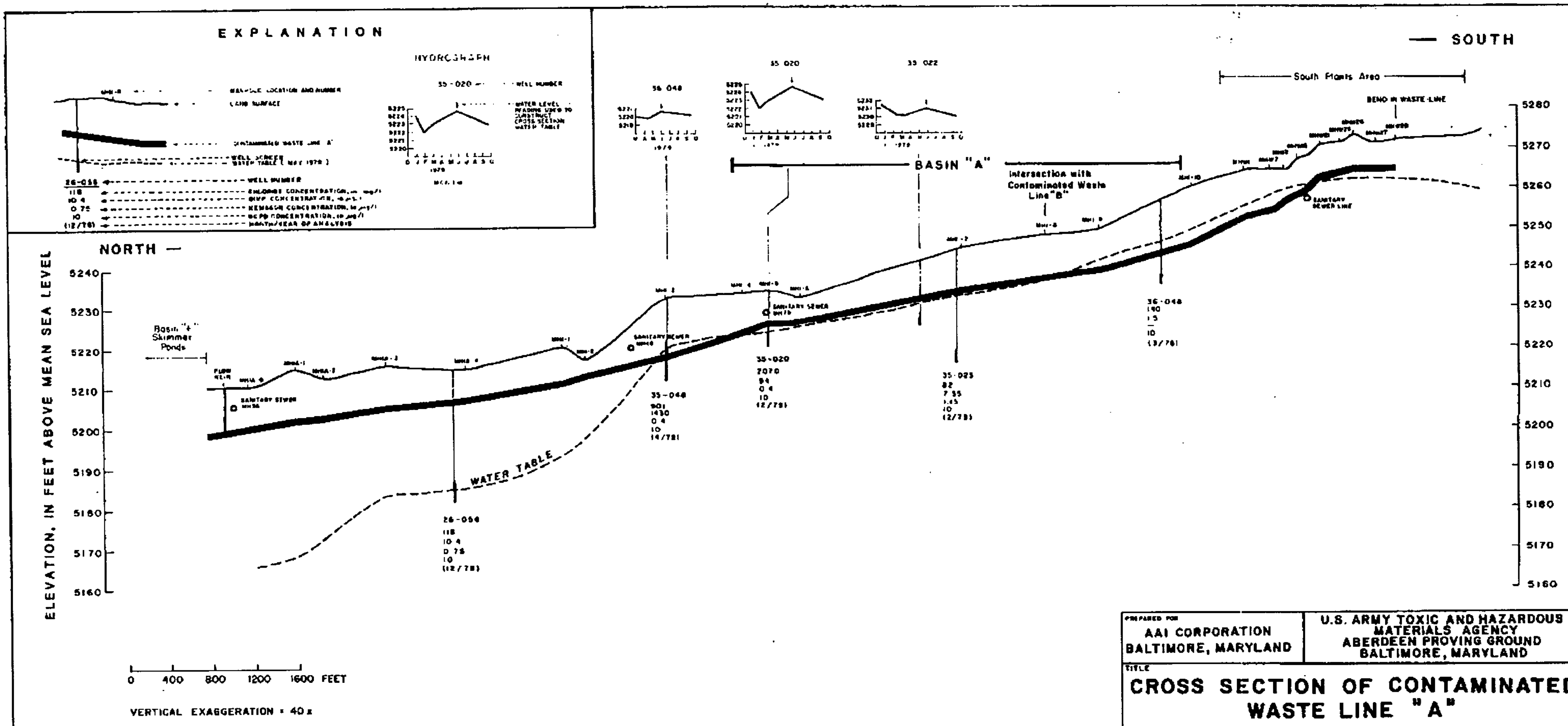

NOTE: ELEVATION OF WATER TABLE FROM WATER TABLE MAP, AS WELLS WERE PROJECTED TO LINE OF SEWER SECTION.

PREPARED FOR
AAI CORPORATION
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ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

TITLE

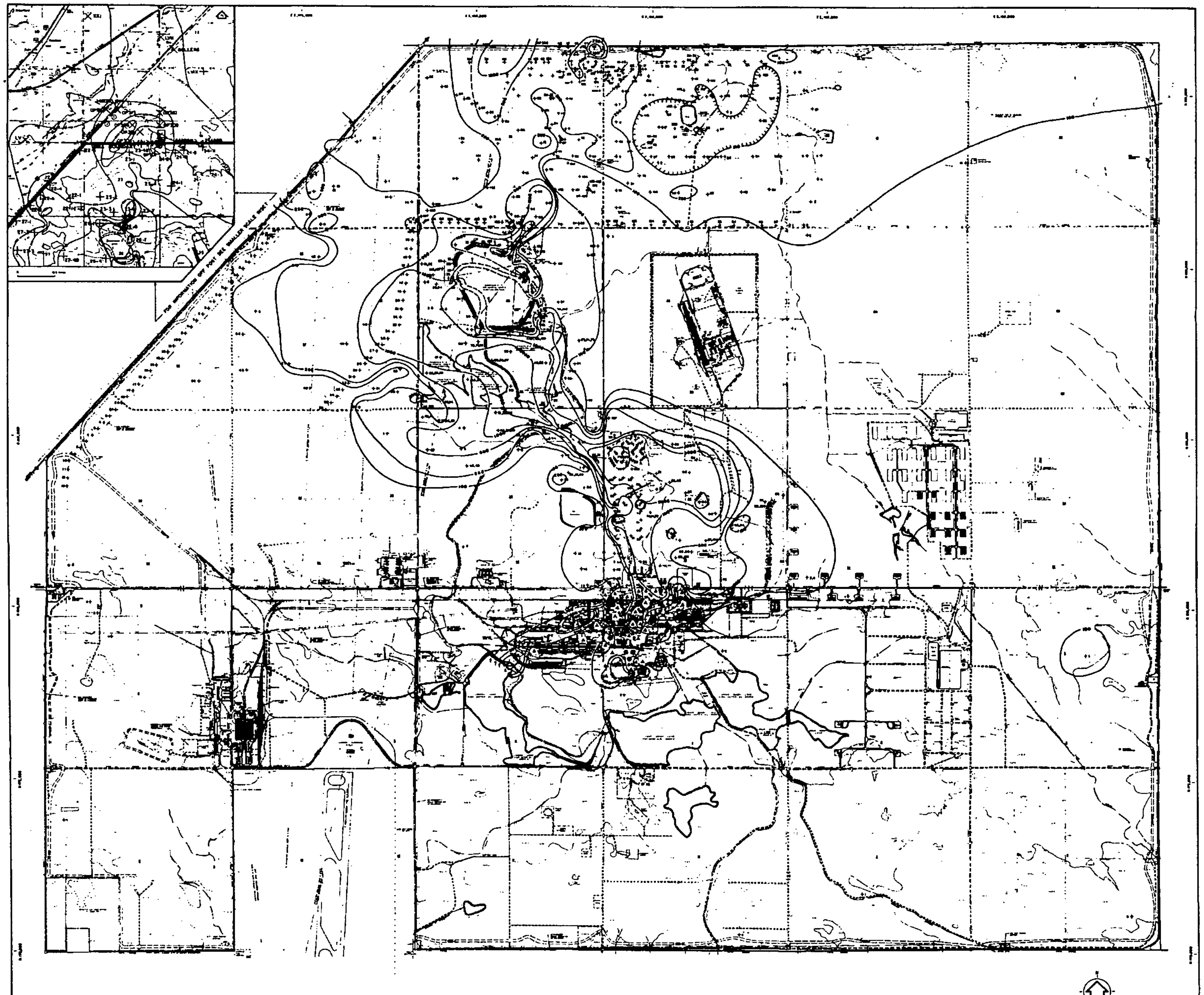
CROSS SECTION OF CONTAMINATED WASTE LINE "A"

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.

COMPILED BY	DANIEL A. NACHMAN	DATE MAR. 1980	PLATE 7
PREPARED BY	WILLIAM H. CICIO	SCALE SHOWN	
PROJECT MANAGER	ROBERT L. STOLLAR		

484-7



EXPLANATION

50 Line of Equal Chemical Concentration in µg/L

▲ Shell Chemical Co. Wells

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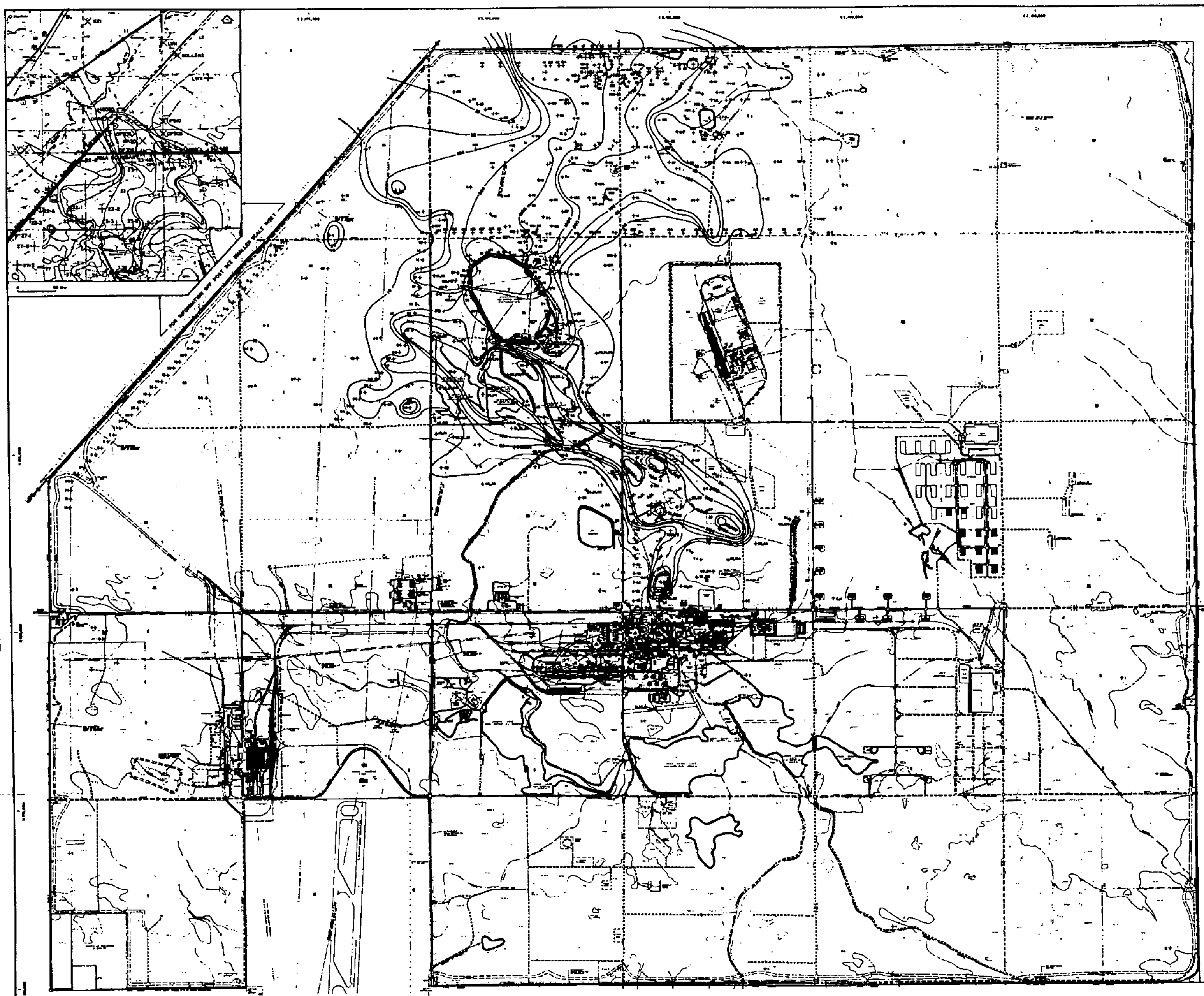
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

LATERAL DISTRIBUTION OF CHLORIDE

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeCillis	January 1981	8
	Robert L. Stoller	Shown	



EXPLANATION

1.0 Line of Equal Chemical Concentration in $\mu g/L$

Shell Chemical Co. Wells

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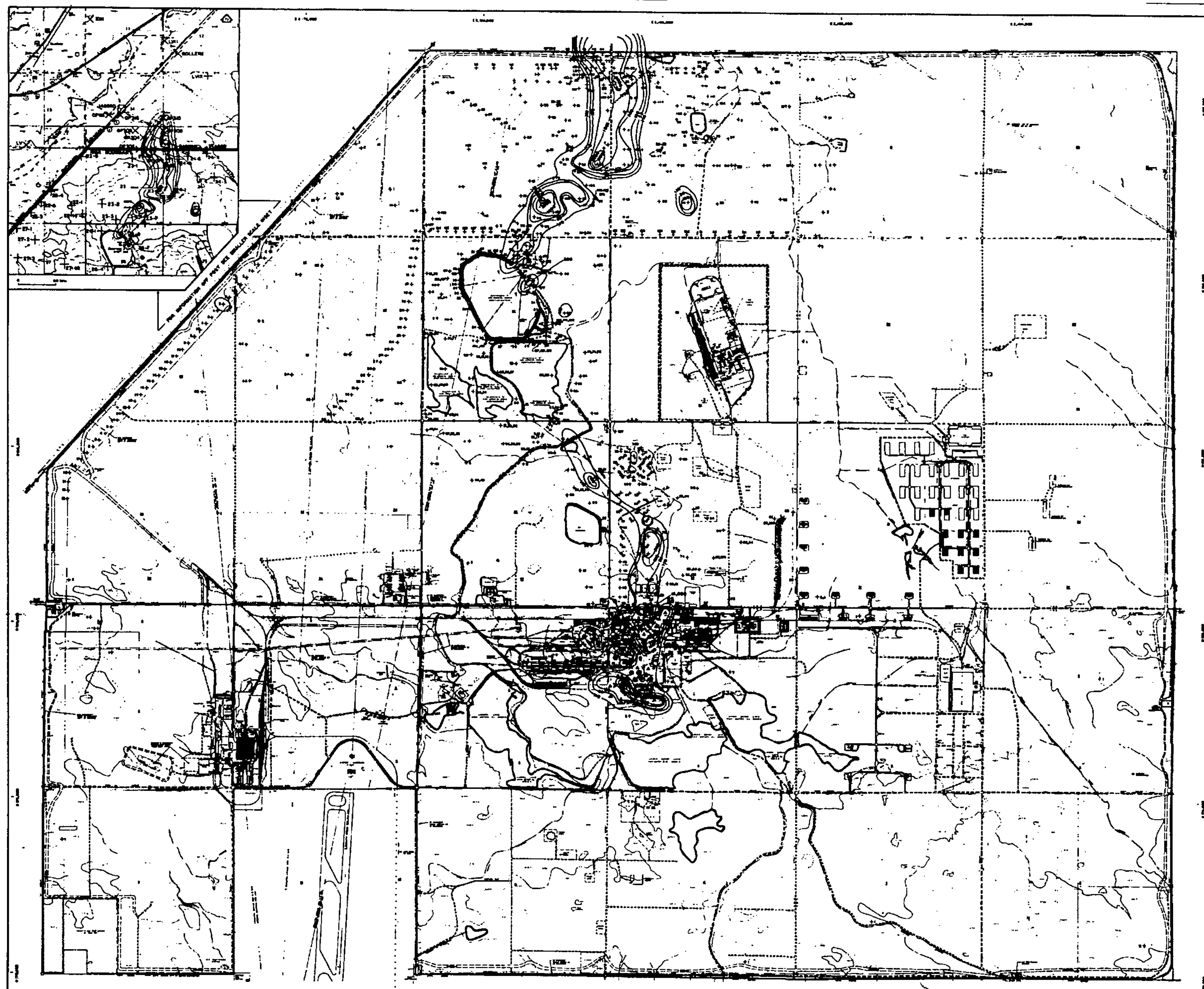
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

LATERAL DISTRIBUTION OF DIMP

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeCalla	January 198[illegible]	9
	Connie Robertson and Wm H. Cole	Shown	
	Robert L. Stoller		



EXPLANATION

Line of Equal Chemical Concentration in $\mu g/L$

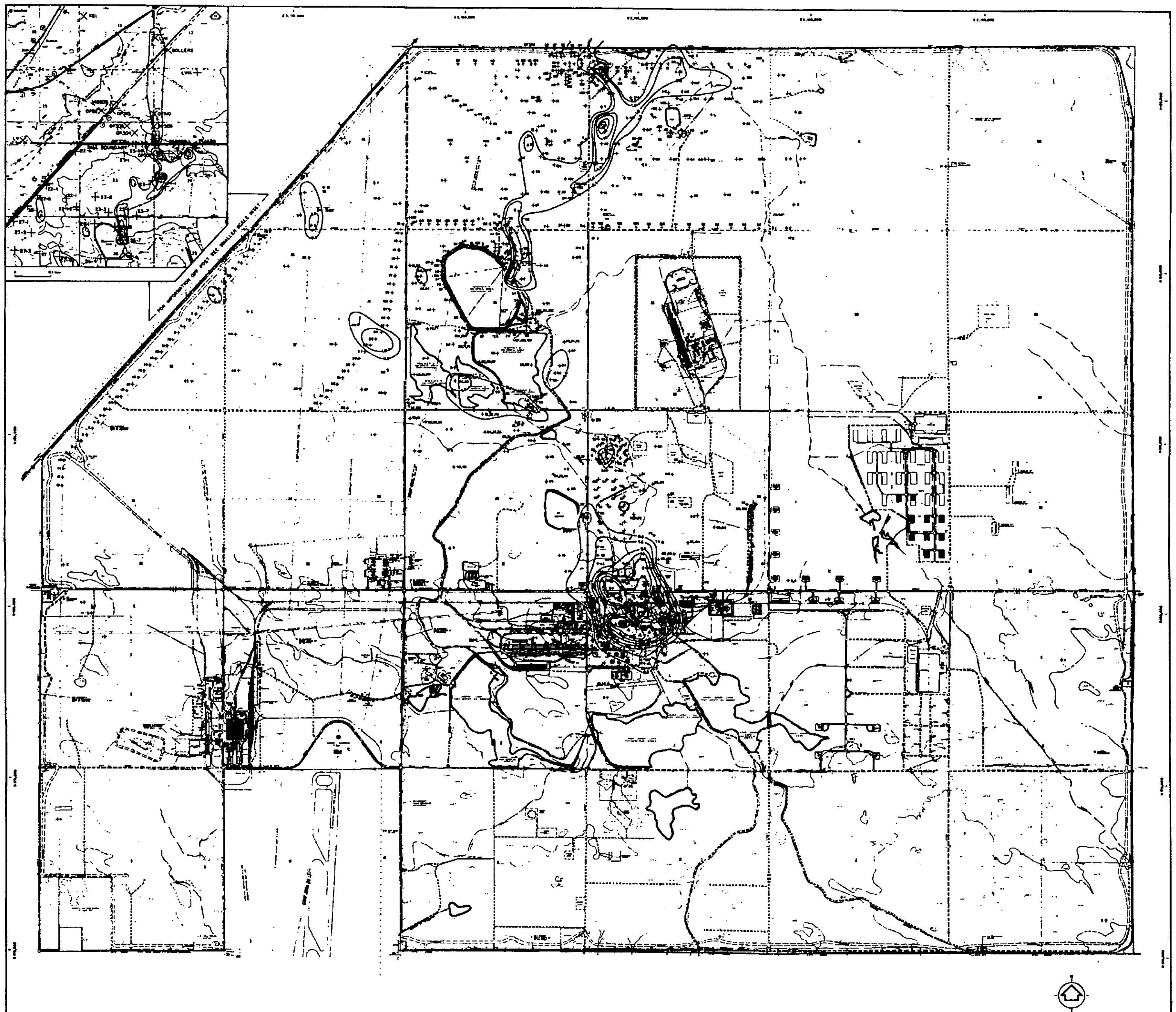
Shell Chemical Co. Wells

AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

LATERAL DISTRIBUTION OF DCPD

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeCillis / Condo Robertson and Wm H Case / Robert L. Stetler	January 1988 / Shown	10



EXPLANATION

—100— Line of Equal Chemical Concentration in $\mu g/L$

▲ Shell Chemical Co. Wells

AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

LATERAL DISTRIBUTION OF NEMAGON

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeCillis	January 198[illegible]	11
	[illegible]	Shown	
	Robert L. Stoller		

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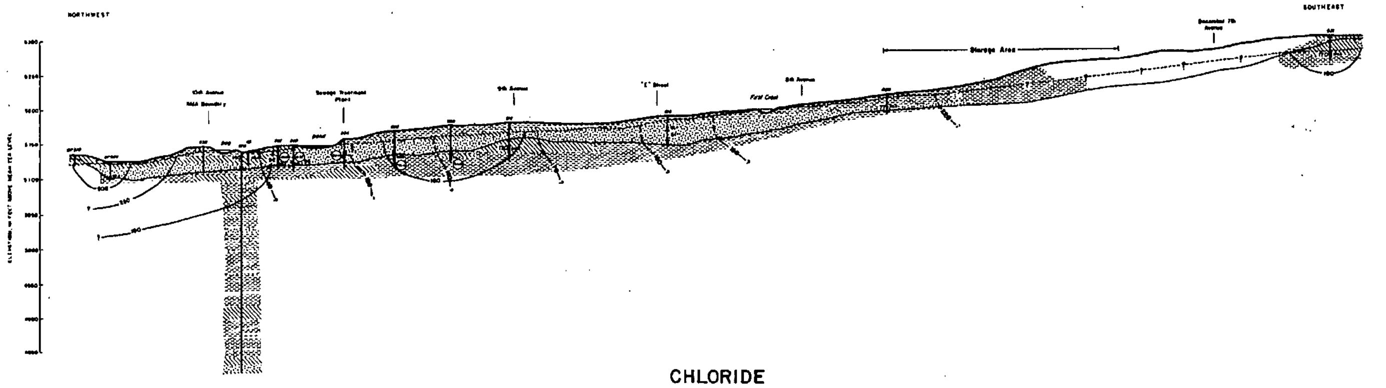
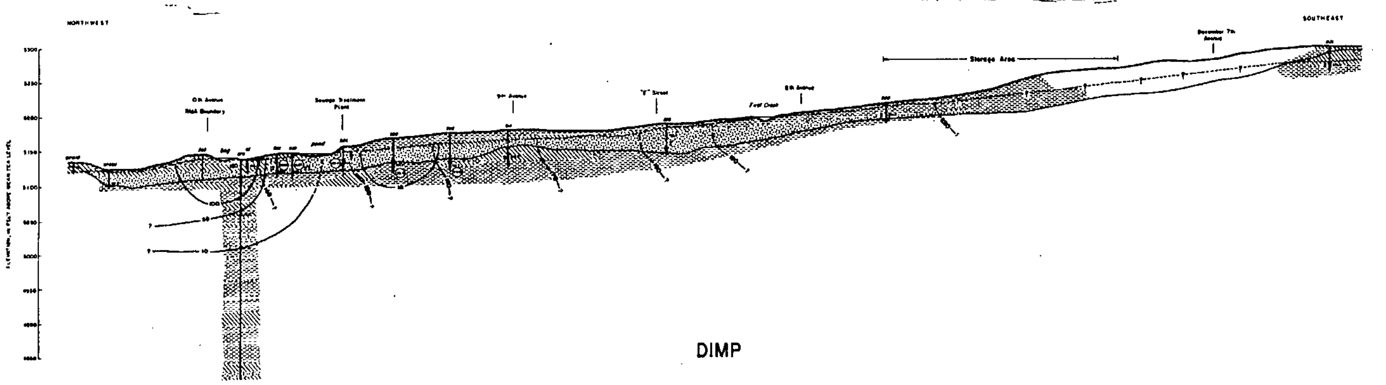
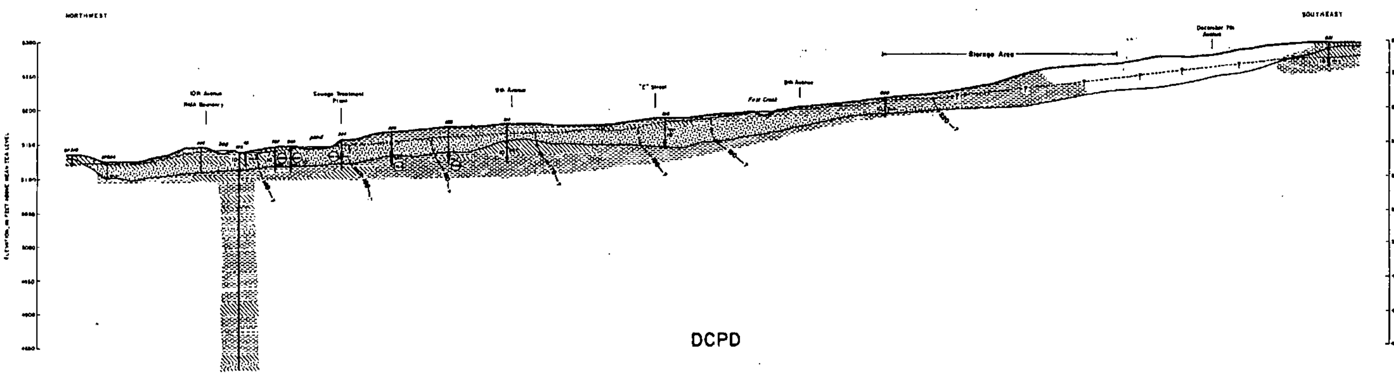


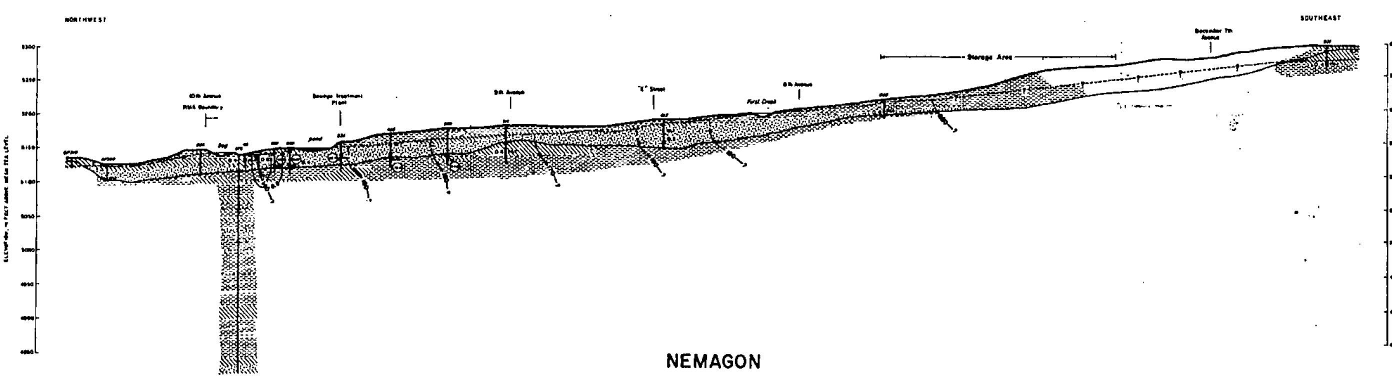
CHLORIDE



DIMP



DCPD



NEMAGON

EXPLANATION

—0.6— LINE OF EQUAL CHEMICAL CONCENTRATION (1979)

D 4a MEASURED 1978

D 4b MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in μg/L
DCPD CONCENTRATION, in μg/L
NEMAGON CONCENTRATION, in μg/L

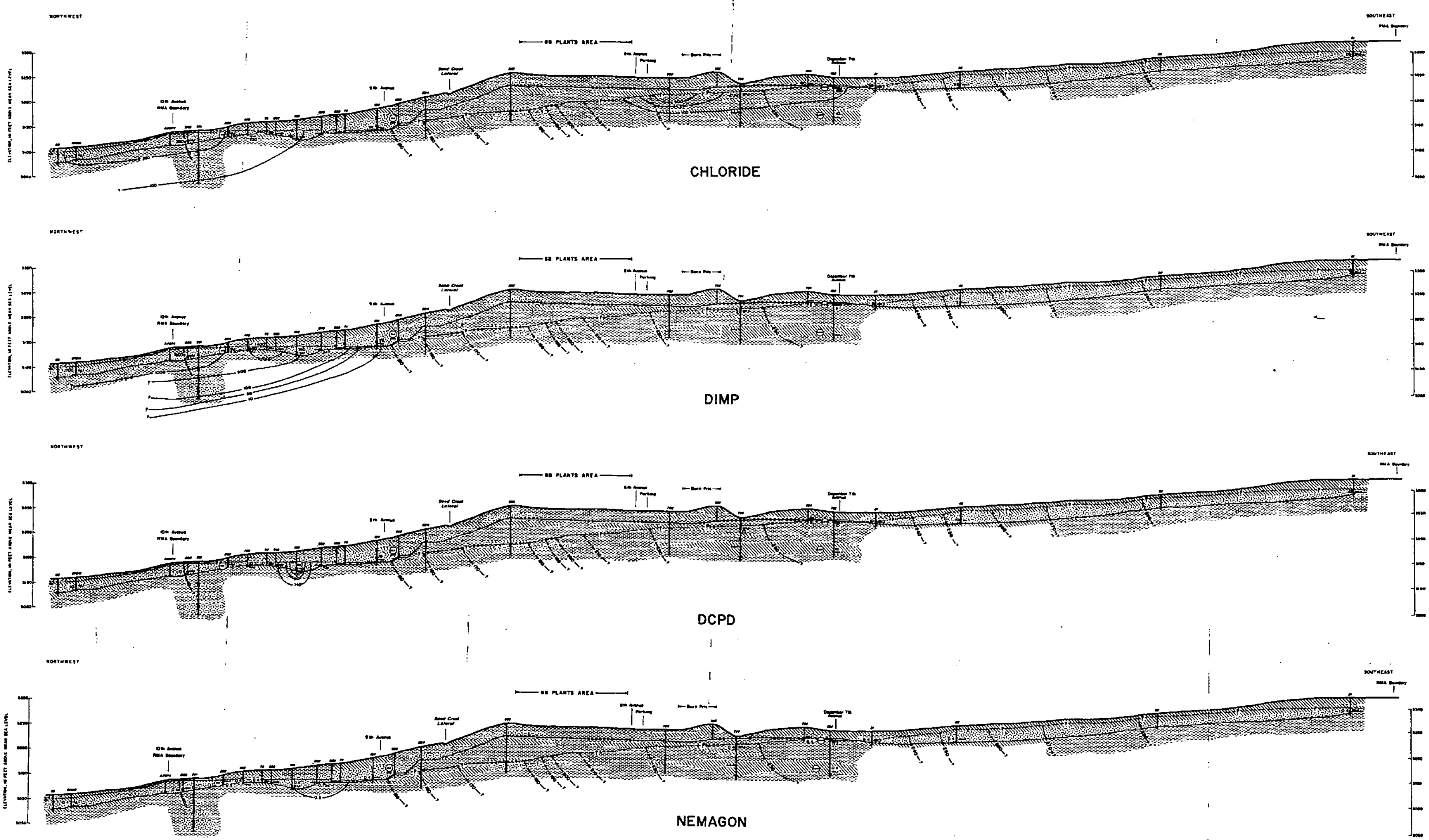
0 1000 2000 FT.

AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER
SECTION I

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeCillis	January [illegible]	12
	Candie Albertson and Wm. H. Dale	Shown	
	Robert L. Stoller		



EXPLANATION

LINE OF EQUAL CHEMICAL CONCENTRATION (1979)
MEASURED 1978
MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in μg/L
DCPD CONCENTRATION, in μg/L
NEMAGON CONCENTRATION, in μg/L

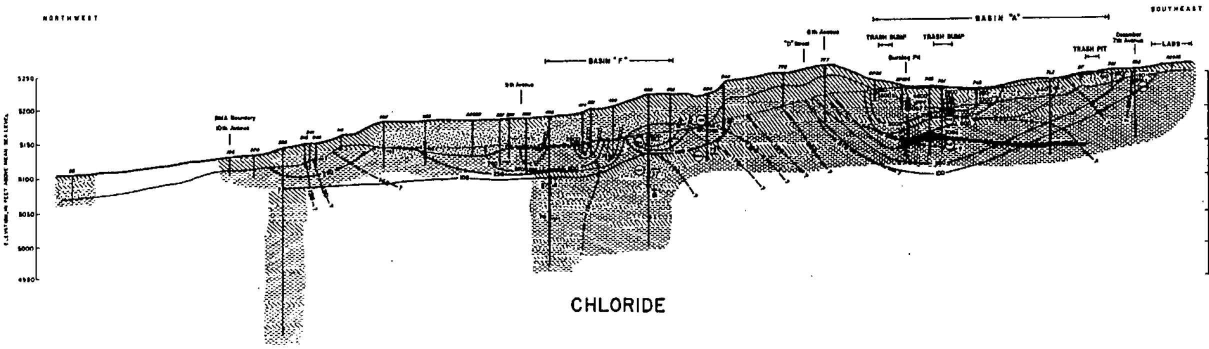
0 1600 3200 FT.

AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

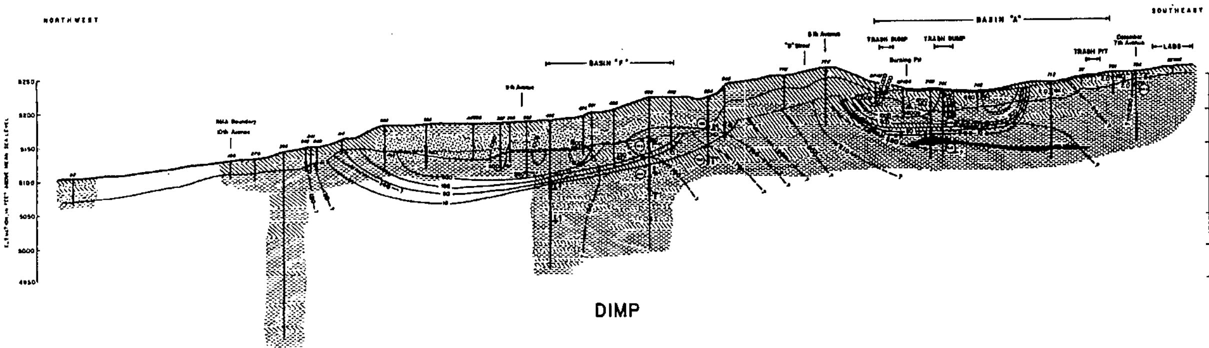
VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER
SECTION II

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

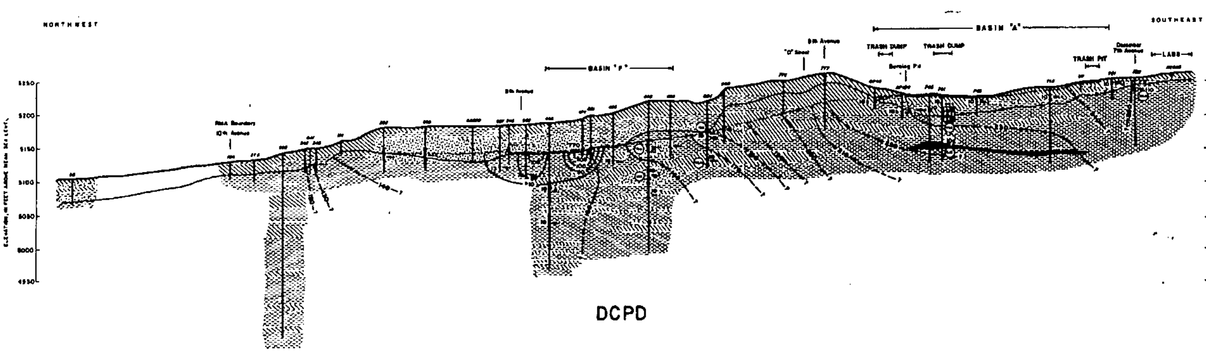
Geraghty & Miller, Inc.	Michael A. DeCaire	January 1981	13
	Connie Robertson and Wm. H. Case		
	Robert L. Stoller	Shown	



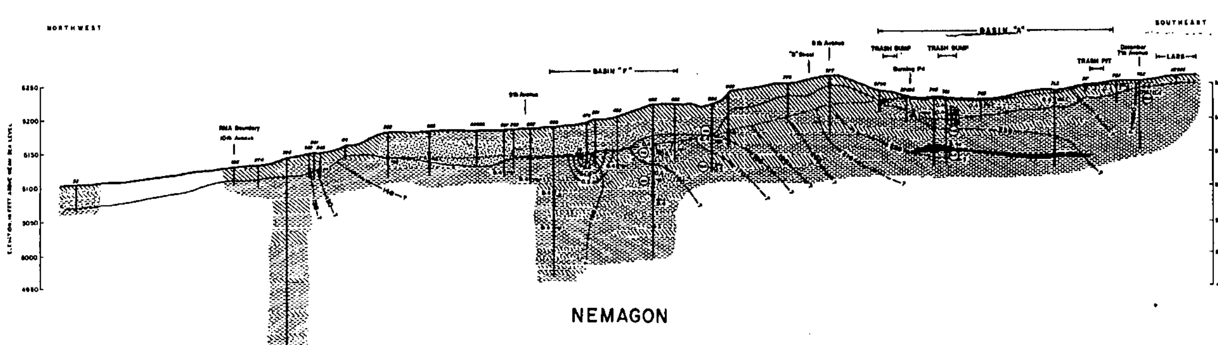
CHLORIDE



DIMP



DCPD



NEMAGON

EXPLANATION

- LINE OF EQUAL CHEMICAL CONCENTRATION (1979)
- MEASURED 1976
- MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in µg/L
DCPD CONCENTRATION, in µg/L
NEMAGON CONCENTRATION, in µg/L

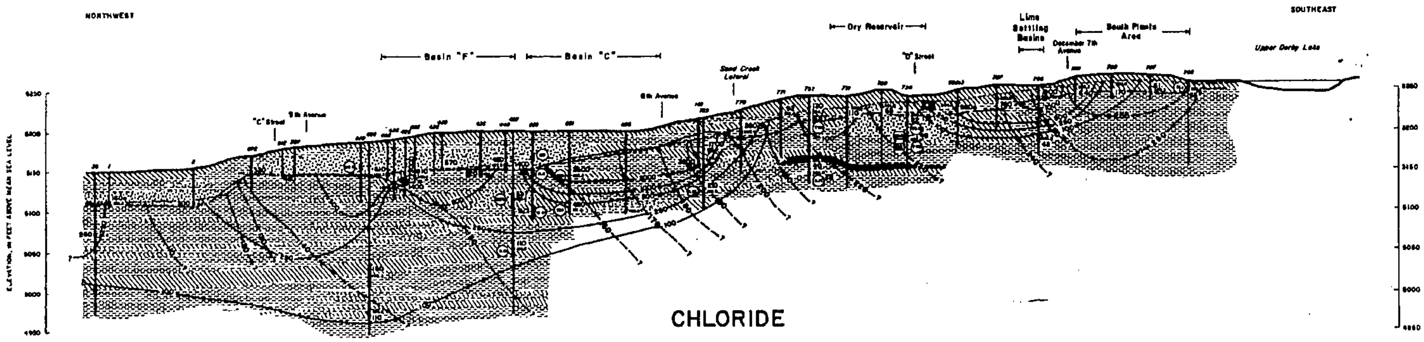
0 1000 2000 Ft

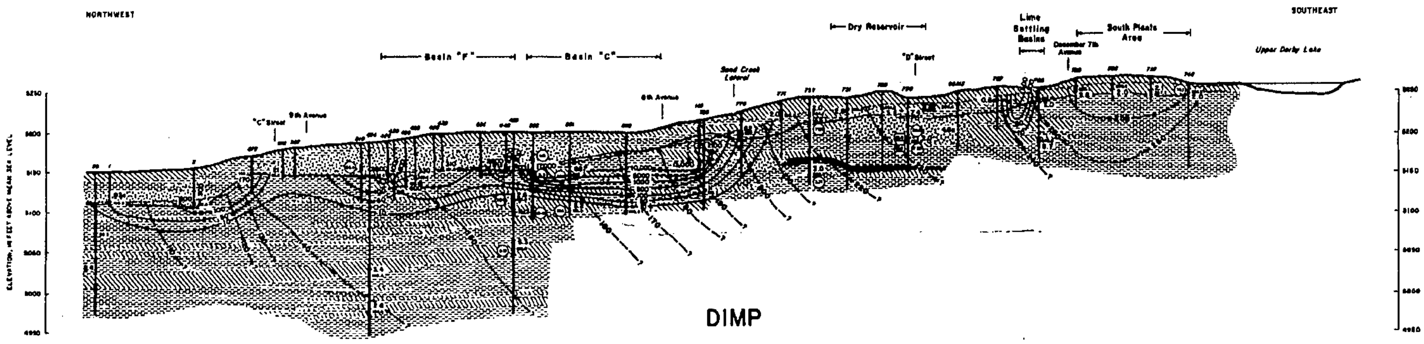
AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

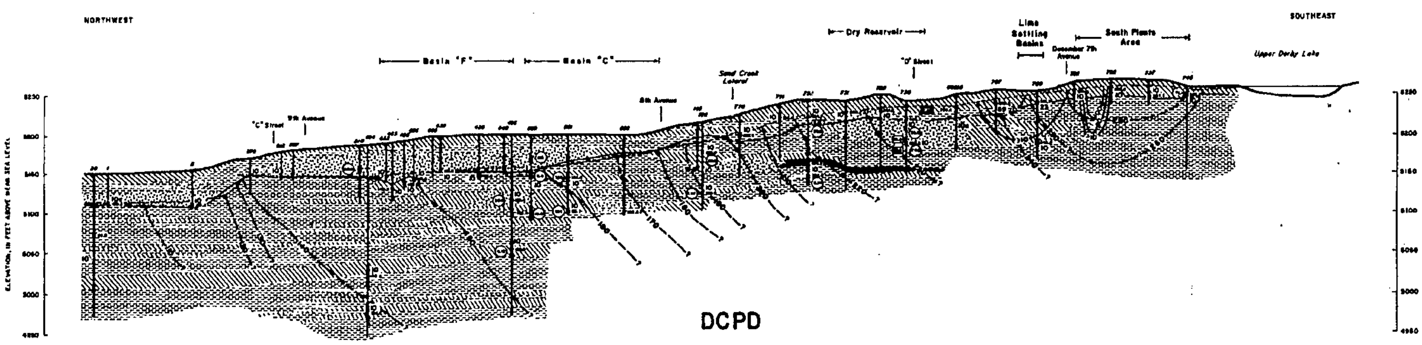
VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER
SECTION III

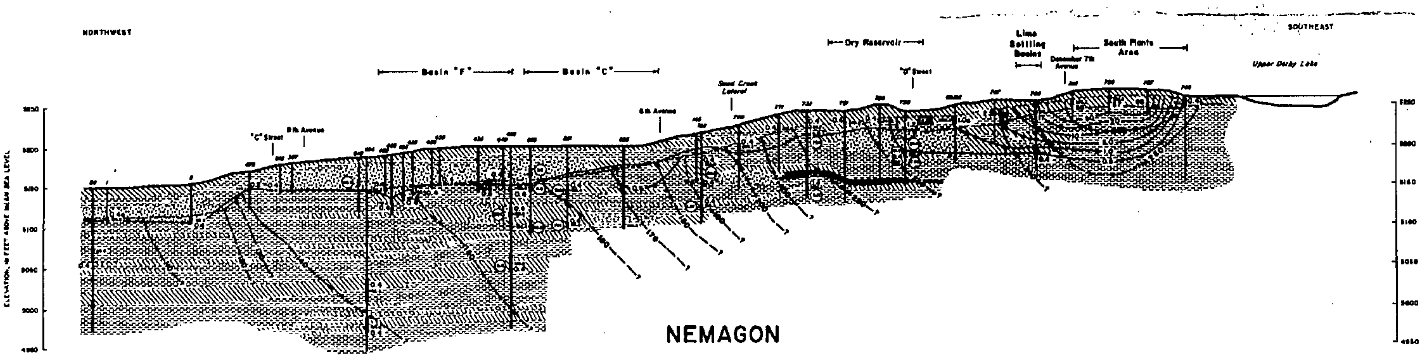
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeCillis	January 1981	14
	Carole Robertson and Wm.H.Dale	Shown	
	Robert L. Stollar		









EXPLANATION

—0.5— LINE OF EQUAL CHEMICAL CONCENTRATION (1979)

0.4a MEASURED 1978

0.4b MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in μg/L
DCPD CONCENTRATION, in μg/L
NEMAGON CONCENTRATION, in μg/L

0 1600 3200 Ft

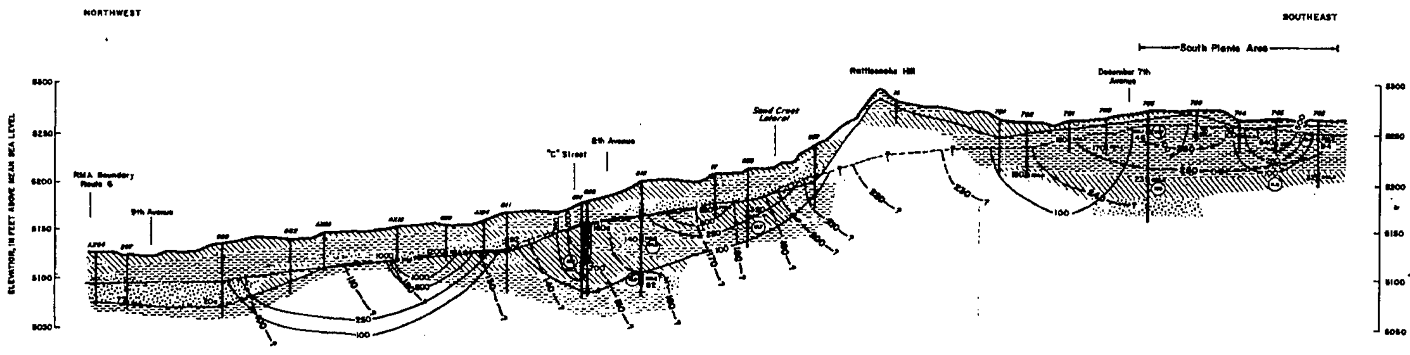
PREPARED FOR AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

TITLE

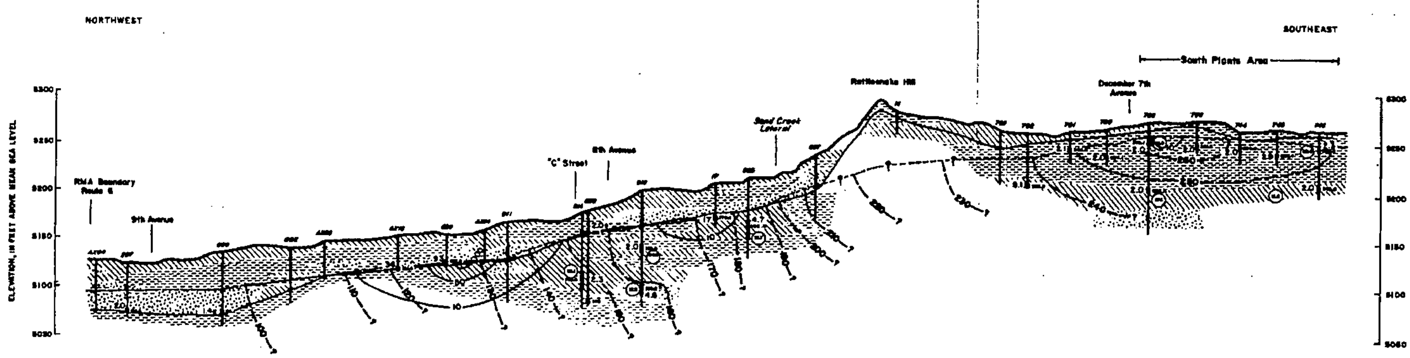
VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER SECTION IV

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

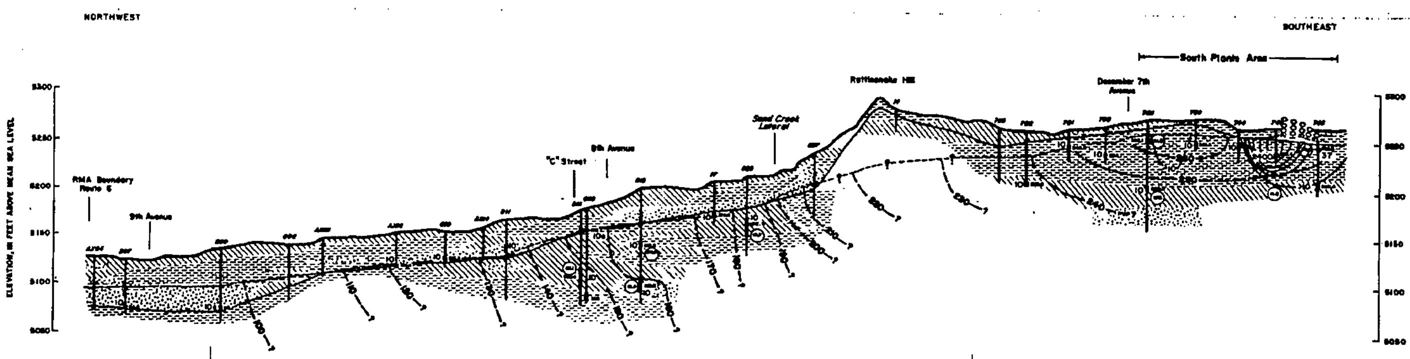
Geraghty & Miller, Inc.	Michael A. DeCillis	DATE January 1981	PLATE 15
	PREPARED BY Carole Robertson and Wm. H. Cole	SCALE Shown	
	Robert L. Stollar		



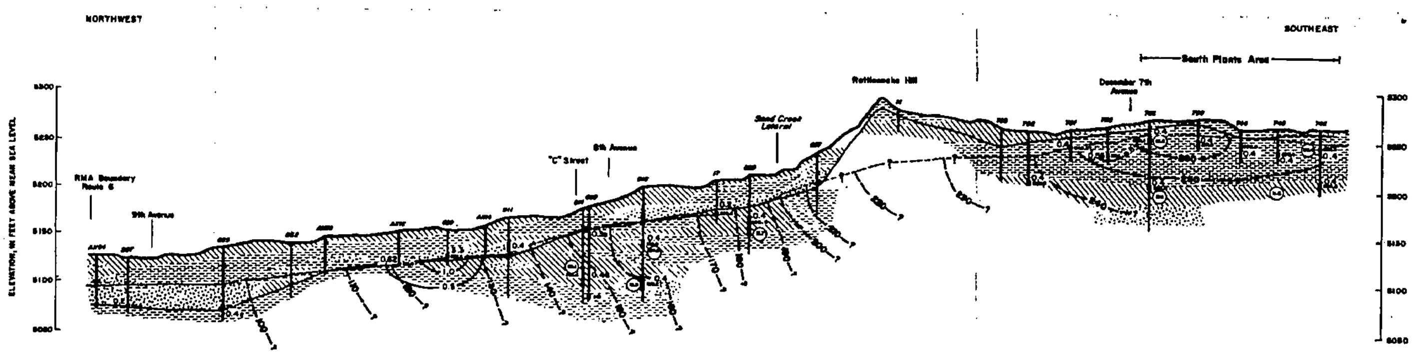
CHLORIDE



DIMP



DCPD



NEMAGON

EXPLANATION

—0.6— LINE OF EQUAL CHEMICAL CONCENTRATION (1979)

0.4a MEASURED 1978

0.4b MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in μg/L
DCPD CONCENTRATION, in μg/L
NEMAGON CONCENTRATION, in μg/L

0 1600 3200 Ft.

PREPARED FOR
AAI CORPORATION
BALTIMORE, MARYLAND

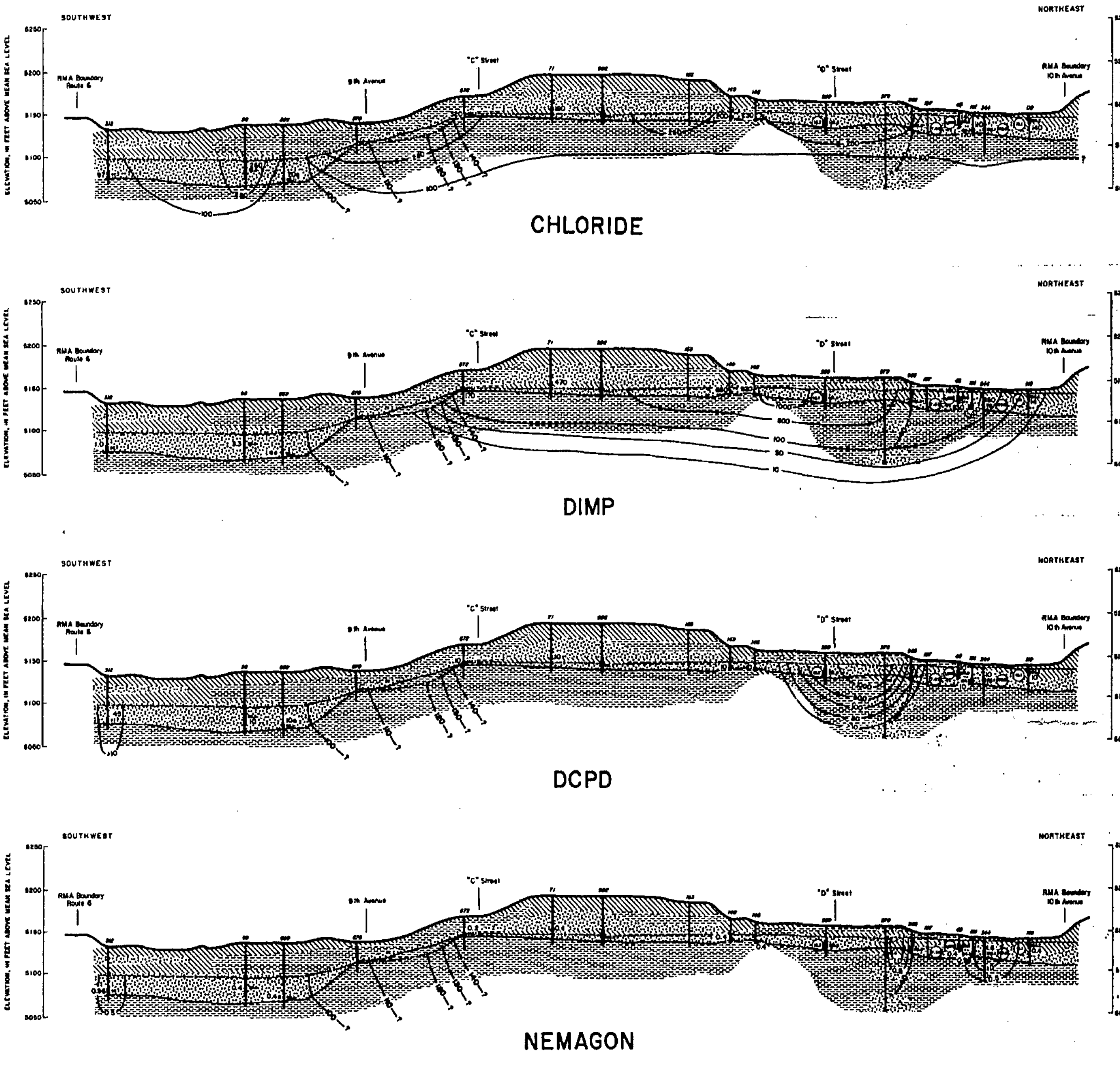
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

TITLE

VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER SECTION V

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY Michael A. DeCillis	DATE January 1981	PLATE 16
	PREPARED BY Candie Robertson and Wm. H. Clair	SCALE Shown	
	PROJECT MANAGER Robert L. Stollar		



EXPLANATION

—0.5— LINE OF EQUAL CHEMICAL CONCENTRATION (1979)

0.4a MEASURED 1978

0.4b MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in µg/L
DCPD CONCENTRATION, in µg/L
NEMAGON CONCENTRATION, in µg/L

0 1600 3200 Ft.

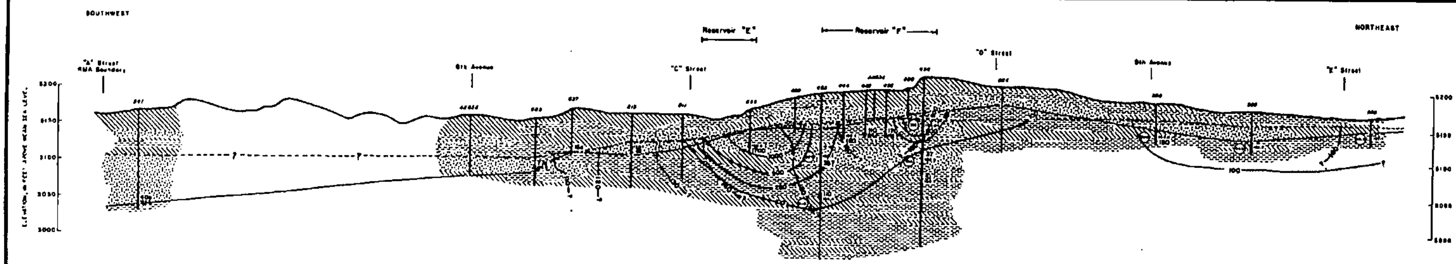
PREPARED FOR AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

TITLE

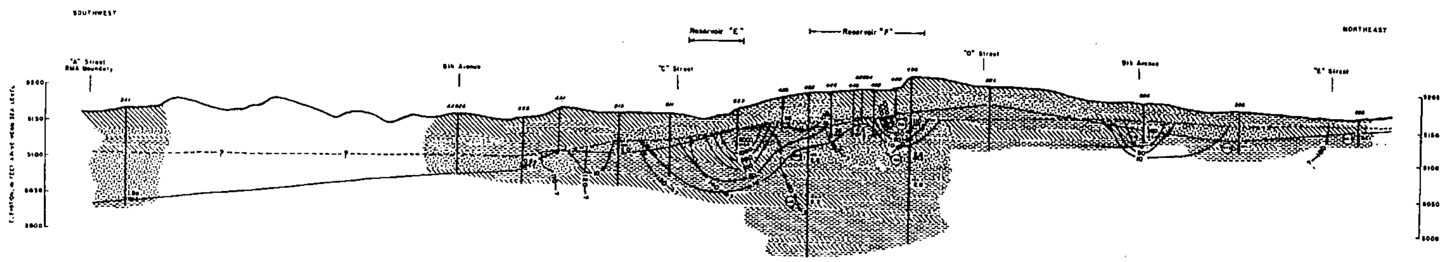
VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER SECTION VI

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

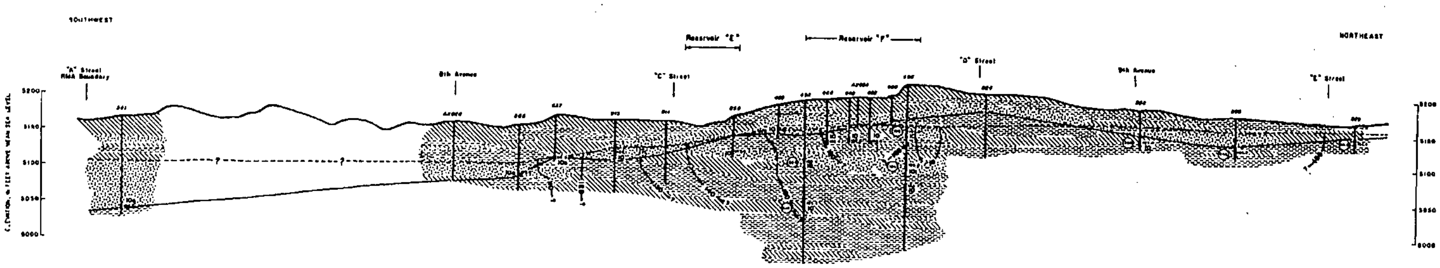
Geraghty & Miller, Inc.	COMPILED BY	Michael A. DeCillis	DATE January 1981	PLATE 17
	PREPARED BY	Candie Robertson and Wm. H. Clair		
	PROJECT MANAGER	Robert L. Stollar	SCALE Shown	



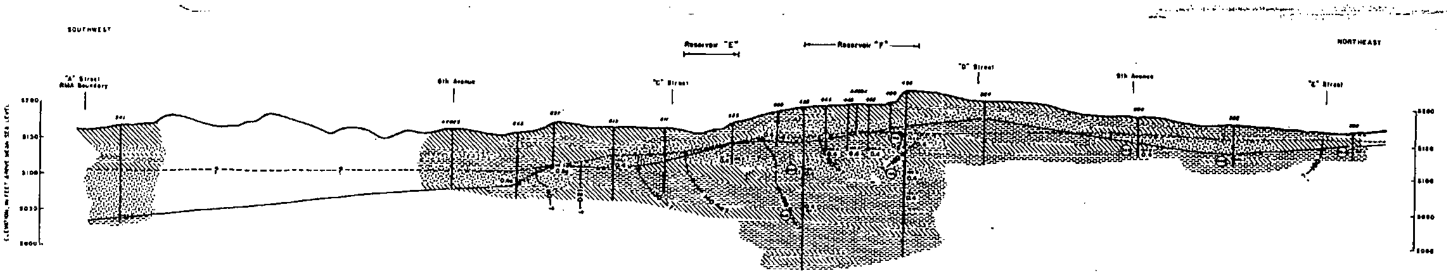
CHLORIDE



DIMP



DCPD



NEMAGON

EXPLANATION

0.5 — LINE OF EQUAL CHEMICAL CONCENTRATION (1978)
0.4a MEASURED 1978
0.1b MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in µg/L
DCPD CONCENTRATION, in µg/L
NEMAGON CONCENTRATION, in µg/L

0 1000 2000 FT.

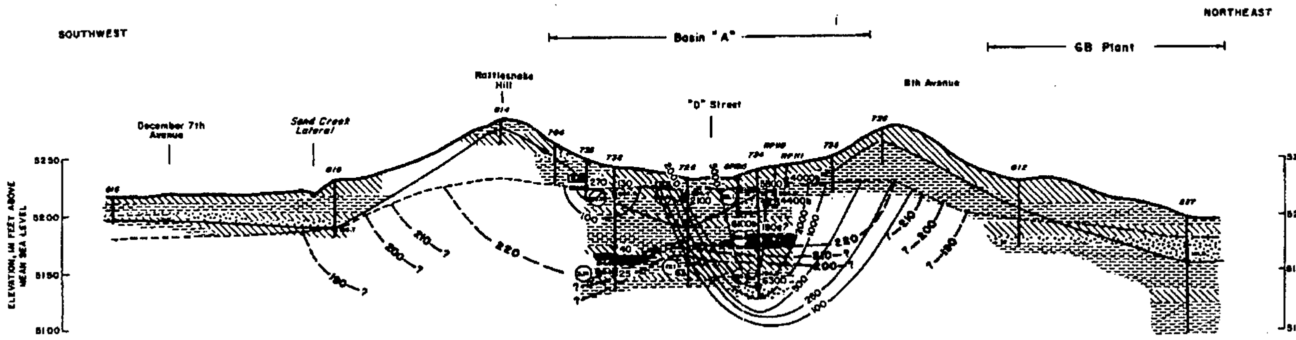
PREPARED FOR
AAI CORPORATION
BALTIMORE, MARYLAND

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

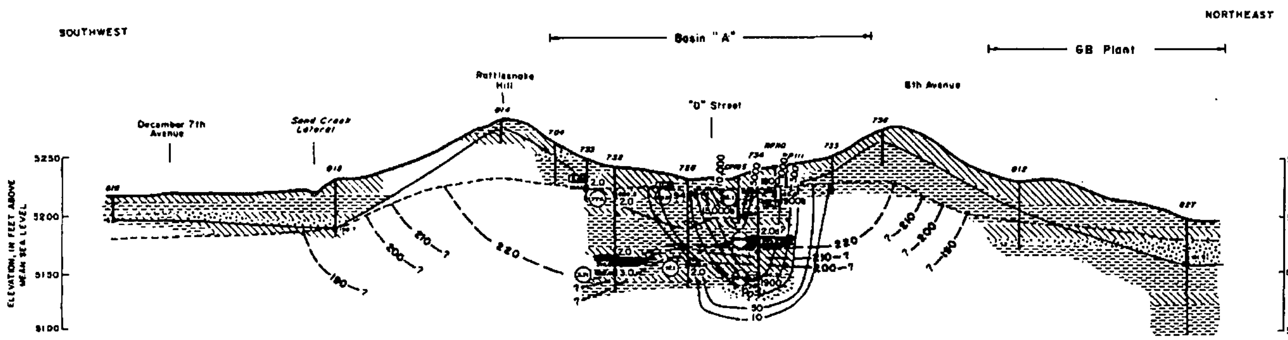
VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER
SECTION VII

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

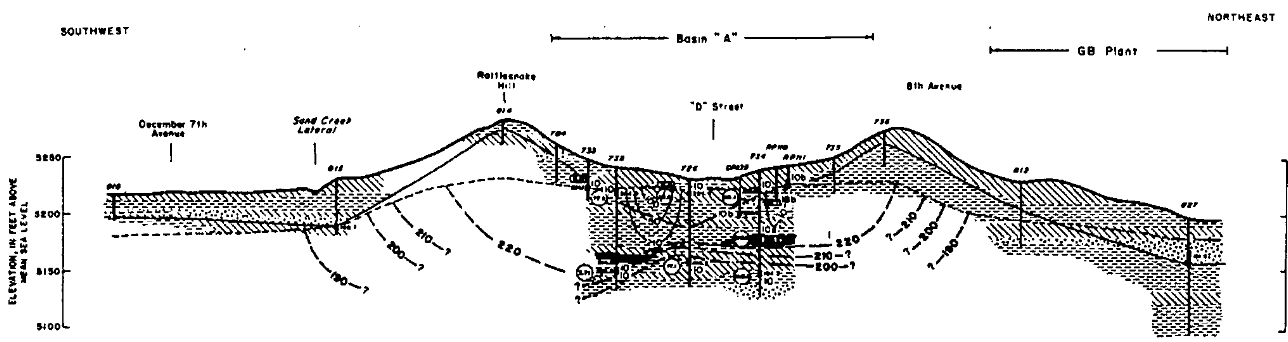
Geraghty & Miller, Inc.	Michael A. DeCillis	January 1981	PLATE 18
	Candie Robertson and Wm.H.Cole	SCALE Shown	
	Robert L. Stoller		



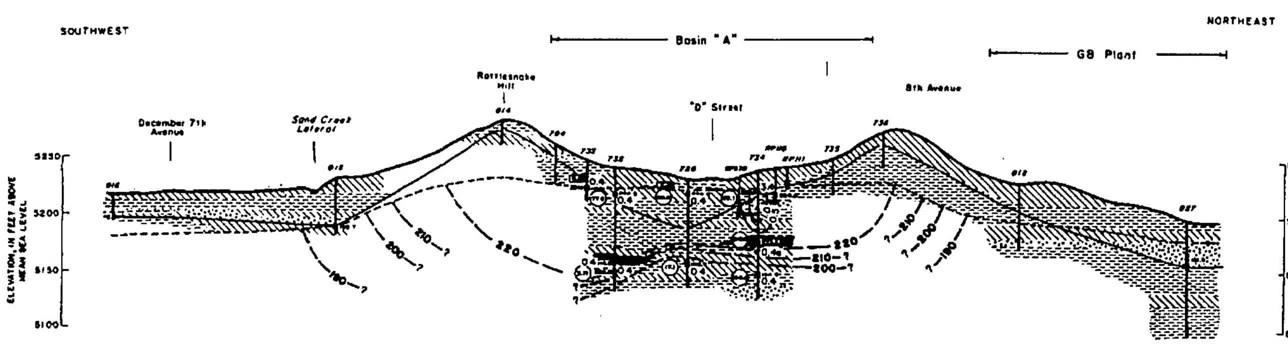
CHLORIDE



DIMP



DCPD



NEMAGON

EXPLANATION

—0.5— LINE OF EQUAL CHEMICAL CONCENTRATION (1979)
0.4a MEASURED 1978
0.4b MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in µg/L
DCPD CONCENTRATION, in µg/L
NEMAGON CONCENTRATION, in µg/L

0 1600 3200 FT.

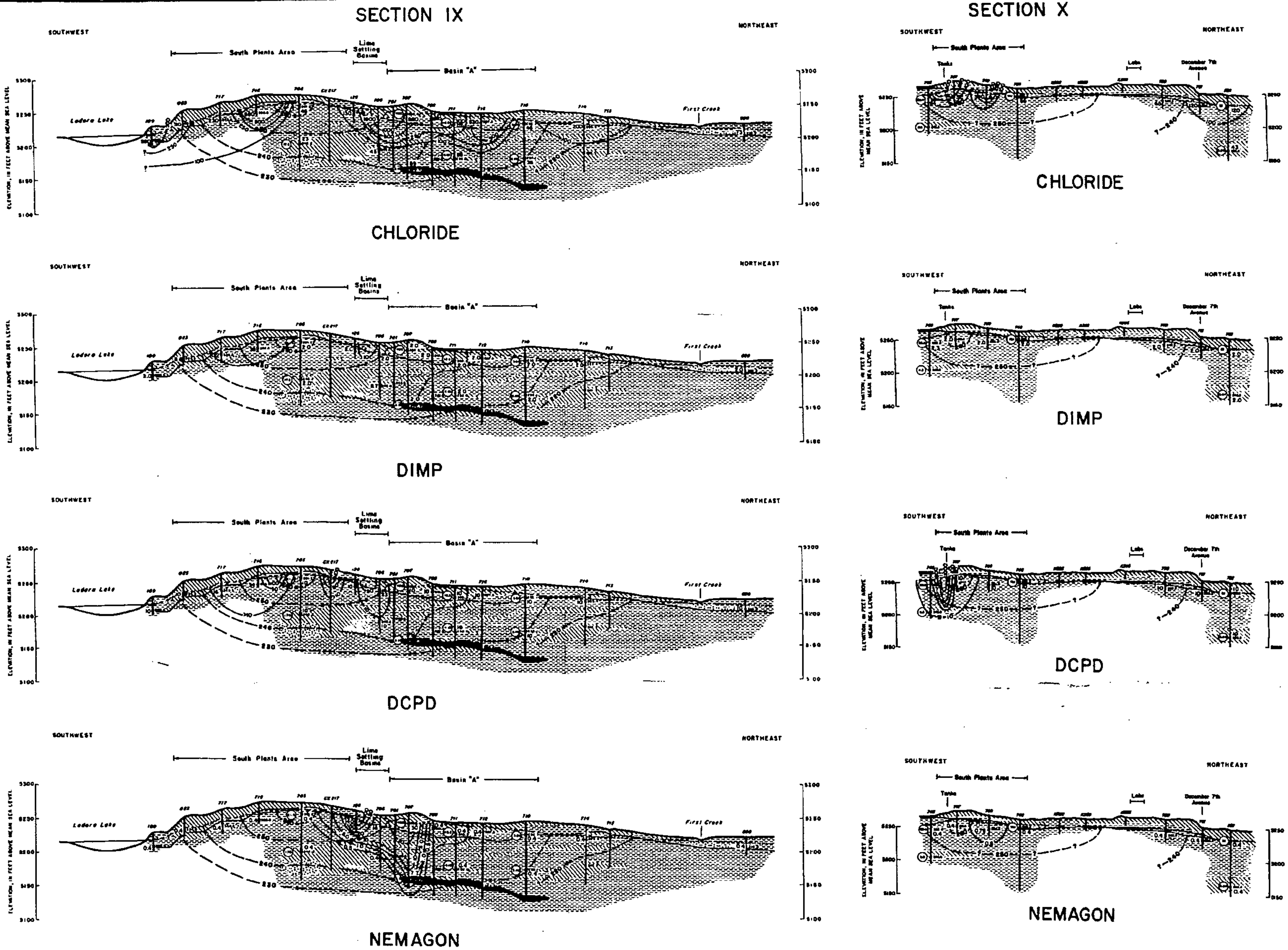
PREPARED FOR: AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

TITLE

VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER SECTION VIII

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY: Michael A. DeCillis	DATE: January 1981	PLATE	19
	PREPARED BY: Candie Robertson and Wm H. Cice			
	PROJECT MANAGER: Robert L. Stollar	SCALE: Shown		



EXPLANATION

—0.5— LINE OF EQUAL CHEMICAL CONCENTRATION (1979)
0.4a MEASURED 1978
0.4b MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in µg/L
DCPD CONCENTRATION, in µg/L
NEMAGON CONCENTRATION, in µg/L

0 1500 3000 FT

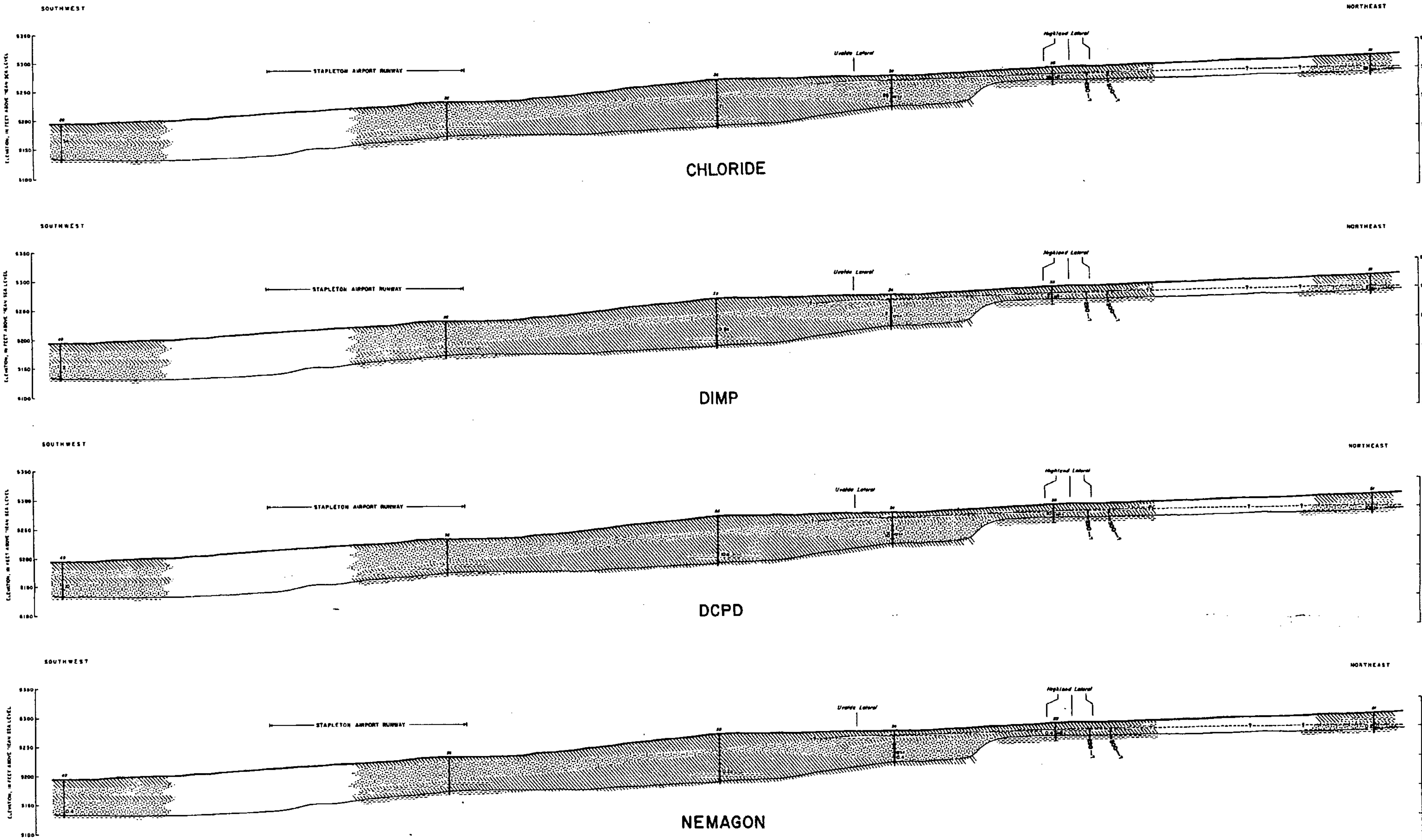
PREPARED FOR: AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

TITLE: **VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER SECTIONS IX & X**

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	COMPILED BY: Michael A. DeCillis	DATE: January 1981	PLATE 20
	PREPARED BY: Candie Robertson and Wendi Cole	SCALE: Shown	
	PROJECT MANAGER: Robert L. Stollar		

007025-00 (20)
B8100084 (20)



EXPLANATION

—— 0.5 —— LINE OF EQUAL CHEMICAL CONCENTRATION (1979)

0 4a MEASURED 1978

0 4b MEASURED 1977

CHLORIDE CONCENTRATION, in mg/L
DIMP CONCENTRATION, in μg/L
DCPD CONCENTRATION, in μg/L
NEMAGON CONCENTRATION, in μg/L

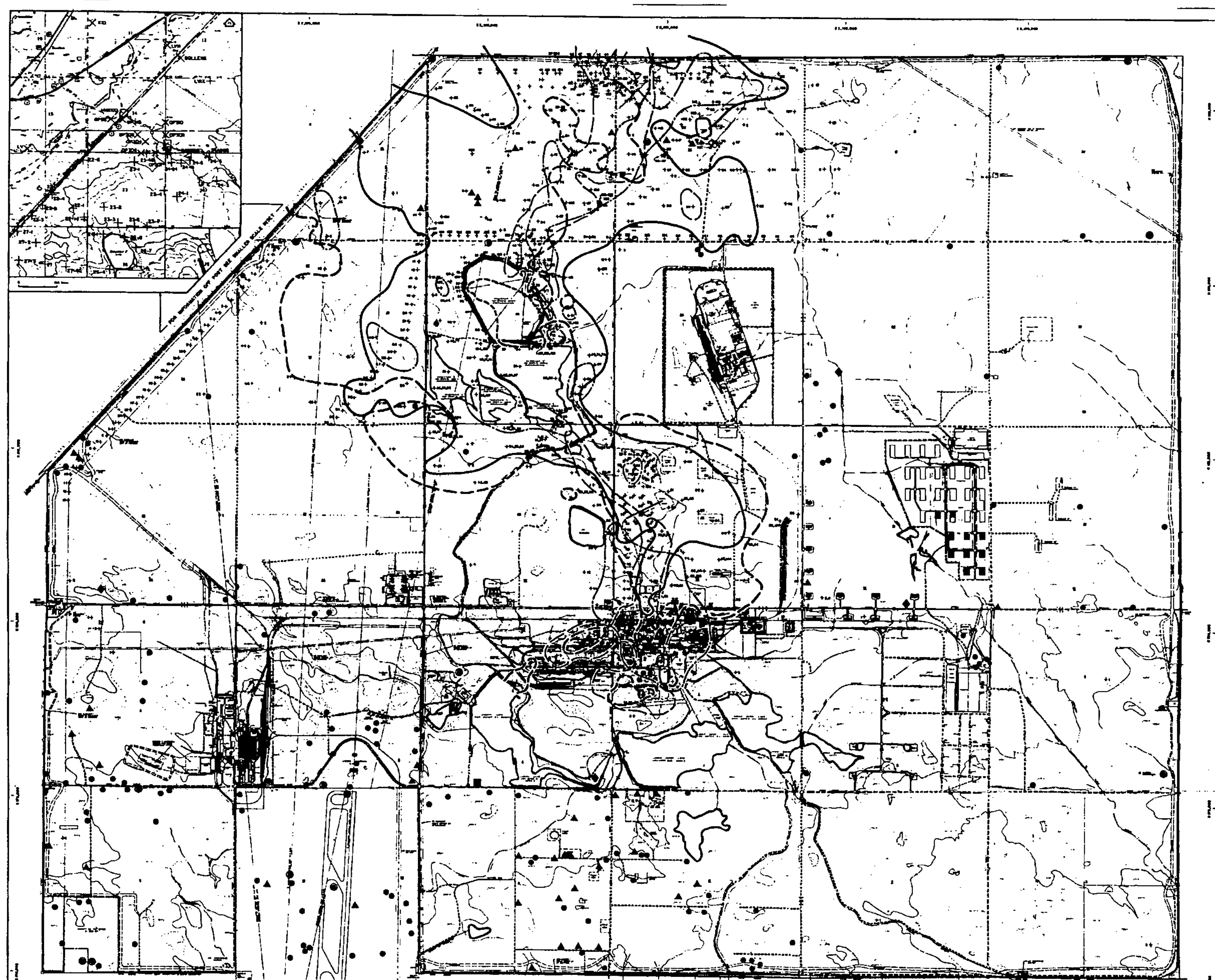
AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

VERTICAL DISTRIBUTION OF CHEMICAL CONSTITUENTS IN GROUND WATER
SECTION XI

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeCillis	January 198[illegible]	21
	Carole Robertson and [illegible]	Shown	
	Robert L. Stoller		

86100054 (21) 007029-09 (21)



EXPLANATION

- ● Well Depth Greater Than 100 Feet
- • Well Depth Less Than 100 Feet
- ▲ Filled Well
- ■ Capped Well
- ◆ Plugged Well

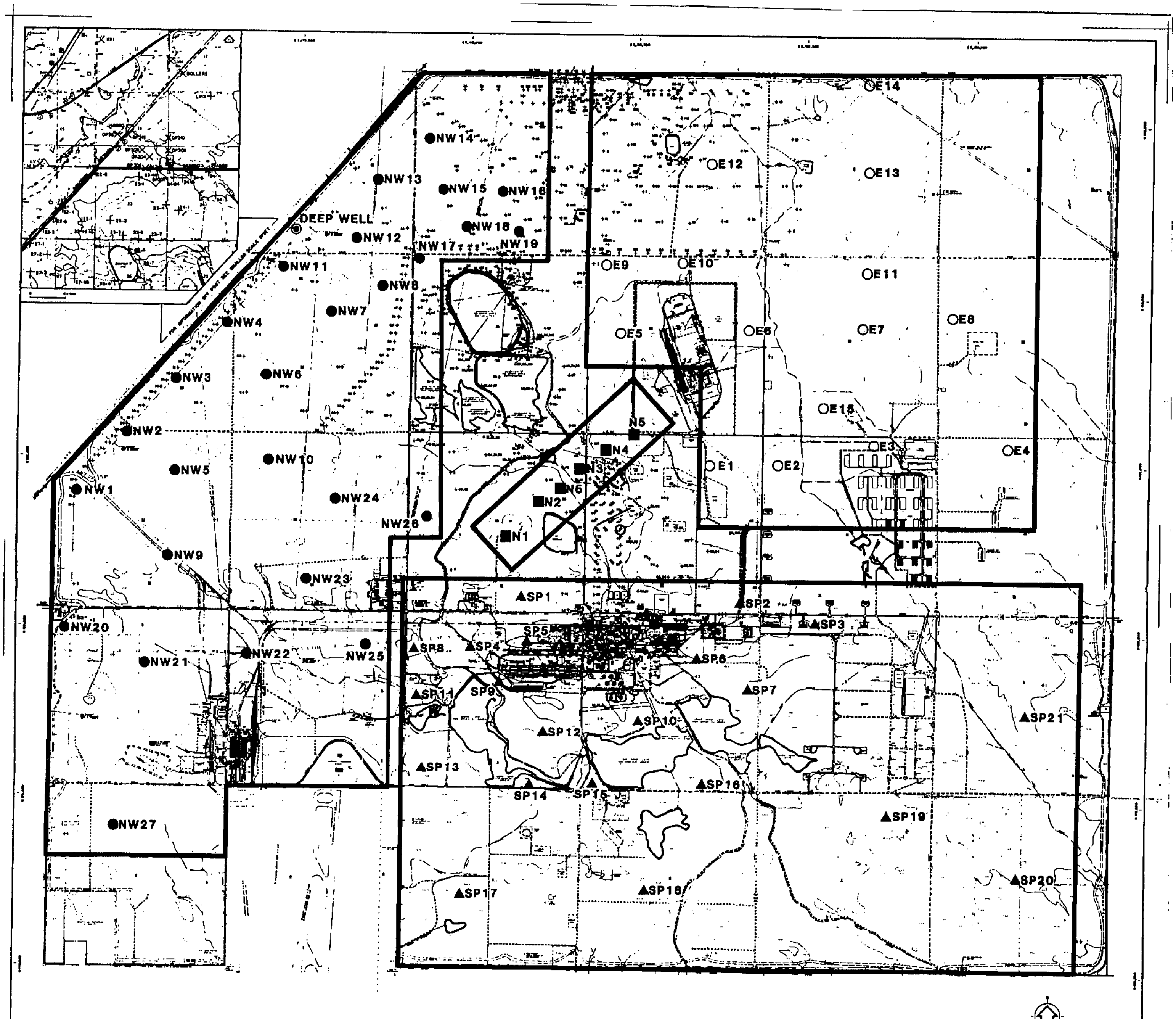
- Outline of Chloride Plume
- Outline of DIMP Plume
- Outline of DCPD Plume
- Outline of Nemagon Plume

AAI CORPORATION BALTIMORE, MARYLAND	U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY ABERDEEN PROVING GROUND BALTIMORE, MARYLAND

LOCATION OF ABANDONED FARM WELLS AND PLUME PATTERNS

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.	Michael A. DeColle	January 198[illegible]	22
	Robert L. Stoller	Shown	



EXPLANATION

- ● NW12 Northwest Boundary Drilling Program
- ▲ SP16 South Plants Drilling Program
- ■ N2 Basin A Neck Drilling Program
- ○ E2 Eastern Arsenal Drilling Program

AAI CORPORATION
BALTIMORE, MARYLAND

U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND
BALTIMORE, MARYLAND

PROPOSED WELL LOCATIONS FOR ARSENAL-WIDE DRILLING PROGRAM

ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Geraghty & Miller, Inc.

Michael A. DeCillis
Carole Amberson and Wm. H Cole
Robert L. Stoller

January 1981

Shown

23

Bibliography on Copyright Educational and Library Fair Use Issues

This bibliography lists some recent publications, articles, brochures, websites and listservs related to copyright educational and library fair use issues that provide information and a variety of perspectives on these issues. This list is not intended to be exhaustive nor does the U.S. Copyright Office necessarily endorse the works listed. Website addresses cited were all correct and active as of March 20, 1999.

Mary Levering
Associate Register for National Copyright Programs
U.S. Copyright Office
May 2000

U.S. Copyright Office Sources:

U.S. Copyright Office. *Copyright Act of 1976*, as amended.
<http://lcweb.loc.gov/copyright/title17/> [U.S. Copyright law. 17 U.S.C. §§ 101, et seq.]

U.S. Copyright Office. *Copyright Basics.* Circular 1, 1996. 12 pp.
<http://lcweb.loc.gov/copyright/circs/> [Copyright Office Circular 1 provides general information and answers some basic questions that are frequently asked about copyright.]

U.S. Copyright Office. *Fair Use*, FL 102 (form letter), December 1994. 1 p.
<http://lcweb.loc.gov/copyright/fls/> [Form letter summarizing basic fair use principles.]

U.S. Copyright Office. *Reproduction of Copyrighted Works by Educators and Librarians.* Circular 21, 1992. 26 pp. <http://lcweb.loc.gov/copyright/circs/>
[This circular includes excerpts from pertinent Congressional documents and legislative provisions relating to fair use and library photocopying in the U.S. copyright law, and other relevant documents dealing with reproduction of copyrighted works by librarians and educators. It includes the 4 sets of educational and library fair use guidelines incorporated in U.S. congressional documents in 1976 and 1981.]

U.S. Copyright Office. Website. <http://lcweb.loc.gov/copyright/>
[Most of the information published by the U.S. Copyright Office on paper is also available for viewing and downloading from the Office's website and gopher site, including information circulars, federal copyright regulations, the Register's testimony, the Office's recent major reports, application forms, and access to Copyright Office records from 1978. To access Copyright Office online databases of copyright records, use <telnet: locis.loc.gov>.]

CONFU (Conference on Fair Use, 1994-98)

U.S. Information Infrastructure Task Force, Working Group on Intellectual Property Rights, Bruce Lehman, Chair. *The Conference on Fair Use: Report to the Commissioner on the Conclusion of the Conference on Fair Use.* Washington, DC. U.S. Patent and Trademark Office. 1998. 189 pp.
<http://www.uspto.gov/web/offices/dcom/olia/confu/>
[The CONFU November 1998 Final Report and the September 1997 First Phase Report document the genesis and history of CONFU, contain proposals for educational fair use guidelines for distance learning (Appendix I), and for digital images (Appendix H), the guidelines adopted for educational multimedia, the uniform preamble accepted by CONFU participants (Appendix G), the "Statement on Use of Copyrighted Computer Programs (Software) in Libraries--Scenarios" (Appendix K), together with all of the individual comments and institutional notifications received concerning the proposals for guidelines and information about the participating organizations.]

U.S. Patent and Trademark Office. CONFU website.
<http:www.uspto.gov/web/offices/dcom/olia/confu/>
[The CONFU website includes the three CONFU reports, plus comments and notifications received in connection with the proposals for educational fair use guidelines.]

Other Sources:

Association of Research Libraries. *Principles For Licensing Electronic Resources.* July 15, 1997.

6 pp. <http://www.arl.org/scomm/licensing/principles.html>

[Six library associations, representing an international membership of libraries of all types and sizes, developed this statement of principles to guide libraries in negotiating license agreements for access to electronic resources so as to create agreements that respect the rights and obligations of both parties.]

Besenjak, Cheryl. *Copyright Plain and Simple.* Franklin Lakes, NJ. Career Press, 1997. 192 pp.

[This handbook on copyright principles and procedures outlines the fundamental elements of copyright in plain and simple language and through practical examples as part of the Career Press "Plain and Simple" series.]

Bruwelheide, Janis H. and Mary Hutchings Reed. *The Copyright Primer for Librarians and Educators.* Chicago, IL: American Library Association, and Washington, DC: National Education Association, 2d edition, 1995. 151 pp.

[Resource book for educators and librarians on fair use, copyright and photocopying for library and educational purposes.]

Consortium for Educational Technology for University Systems. *Fair Use of Copyrighted Works: A Crucial Element in Educating America.* Seal Beach, CA: CSU Chancellor's Office, 1995. 34 pp. [California State University, State University of New York, City University of New York.]

<http://www.cetus.org/fairindex.html>

[A consortium of three major universities, the CSU-SUNY-CUNY Work Group on Ownership, Legal Rights of Use, and Fair Use, address copyright and fair use in the context of higher education, includes analyses of court decisions on educational fair use.]

Crews, Kenneth D. *Copyright Law and Graduate Research: New Media, New Rights and Your Dissertation.* Ann Arbor, MI: UMI Company, 1996. 29 pp.

[This useful manual explains the fundamentals of copyright and is intended to help university students and faculty advisors understand their legal rights and responsibilities regarding the use of others copyrighted works. It explains when to seek copyright permissions and how to obtain them and also provides guidance on how to protect one's own copyrighted works.]

Crews, Kenneth D. *Copyright, Fair Use, and the Challenge for Universities: Promoting the Progress of Higher Education.* Chicago, IL: The University of Chicago Press, 1993. 256 pp.

[An explanation of copyright and the ambiguous concepts of fair use as they affect and are affected by higher education. The first large-scale study of its kind surveys the copyright policies of 98 American research universities and reveals a variety of ways in which universities have responded to--and how they could better manage--the conflicting goals of copyright policies--avoiding infringements while promoting lawful uses that serve teaching and research. *Introduction.*]

Perspectives on ... Fair Use, Education, and Libraries: A Town Meeting to Examine the Conference on Fair Use. Lois Lunin, ed., Kenneth D. Crews and Dwayne K. Buttler, guest eds. Journal of the American Society for Information Science. Vol. 50, 1999. **[In press.]**

[This special issue of *JASIS Perspectives* contains several articles by presenters at the 2d town meeting on fair use, "Fair Use, Education and Libraries: a Town Meeting to Explore the Conference on Fair Use", hosted by the Indiana University Institute for the Study of Intellectual Property and Education and held at the campus of Indiana University-Purdue University in Indianapolis, Indiana, on April 4, 1997.]

Fair Use Guidelines for Educational Multimedia. Nonlegislative Report of the Subcommittee on Courts and Intellectual Property, Committee on the Judiciary, U.S. House of Representatives. September 27, 1996. 12 pp. <http://www.indiana.edu/~ccumc/mmfairuse.html>

[The Consortium of College and University Media Centers coordinated development of these guidelines during 1994-96, together with numerous participating organizations in a parallel initiative to CONFU; these guidelines were completed in September 1996 and acknowledged by the U.S. Congress in this Nonlegislative Report.]

Gasaway, Laura N., editor. *Growing Pains: Adapting Copyright for Libraries, Education and Society.* Littleton, CO: Fred B. Rothman & Co., 1997. 558 pp.

[Collection of 20 essays written by a variety of scholars with expertise in the fields of copyright law, education, and librarianship who advocate changes in the copyright statute, in interpretations of the law, and in school and library practices so that librarians and educators can meet their obligations.]

Gasaway, Laura N. and Sarah K. Wiant. *Libraries and Copyright: A Guide to Copyright Law in the 1990s.* Washington, DC: Special Libraries Association, 1994. 271 pp.

[Both authors are directors of university law libraries and professors of law; this source covers the functions and uses of copyright law, geared primarily to librarians and anyone engaged in the lending of and dissemination of copyrighted works.]

Goldstein, Paul. *Copyright's Highway: From Gutenburg to the Celestial Jukebox.* New York, NY: Hill and Wang, 1994. 261 pp.

[Copyright expert Paul Goldstein, Professor of Law at Stanford University, traces the 300-year old history of copyright, explains the concepts and rationale behind the idea of intellectual property rights, and highlights noteworthy legal battles, (including the famous Williams & Wilkins photocopying case). Booklist, Dec. 1, 1994.]

Hardy, I. Trotter. *Project Looking Forward: Sketching the Future of Copyright in a Networked World-Final Report.* Washington, DC: U.S. Copyright Office, May 1998. 304 pp.

<http://lcweb.loc.gov/copyright/cpypub/thardy.pdf>

[A report commissioned by the U.S. Copyright Office from I. Trotter Hardy, Professor of Law, College of William and Mary, as part of the U.S. Copyright Office's continuing effort to examine the future of the Internet and related digital communication's technologies, and to identify legal and policy issues that might arise as a result. Copies are available from the U.S. Government Printing Office - stock number 030-002-00191-8.]

Harper, Georgia. *Will We Need Fair Use in the Twenty-First Century?* March 4, 1997. 31 pp.

<http://www.utsystem.edu/ogc/intellectualproperty/fair_use.htm>

[Harper, a copyright lawyer in the Office of General Counsel of the University of Texas System, explores the meaning of fair use to "focus attention on those parts of its function that are most affected by the electronic environment; an examination of that effect; an evaluation of the supposed benefits of fair use and alternative ways to achieve those benefits given the impact of the electronic environment on fair use."]

Malero, Marie C. *A Legal Primer on Managing Museum Collections.* Washington, DC: Smithsonian Institution Press, 2 ed. 1998.

[This source has an informative 50-page discussion on copyright issues for museums, written by former Smithsonian Institution Assistant General Counsel Ildiko DeAngelis.]

Shapiro, Michael S. and Brent I. Miller. *A Museum Guide to Copyright and Trademark.* Washington, DC: American Association of Museums, 1999. 226 pp.

[This *Museum Guide* is designed to guide informed decisions by museums about how to manage intellectual property owned by the museums and that of others that museums hold in trust, and how to establish best practices for developing institutional policy and procedural statements.]

Templeton, Brad. *10 Big Myths About Copyright Explained: An Attempt to Answer Common Myths About Copyright Seen on the Net.* <http://www.templetons.com/brad/copymyths.html>

[This web-based essay by a publisher of an electronic newspaper on the net is an attempt to answer common "myths" about copyright seen on the Net and covers issues related to copyright and Usenet/Internet publication.]

Websites (with copyright information)

These websites contain references, links, and additional informational resources and opinions on copyright, educational and library fair use issues. Many of these sites have links to other informational materials with related copyright themes.

Fair Use Guidelines for Educational Multimedia. <http://www.indiana.edu/~ccumc/mmfairuse.hml>
[Development of these fair use guidelines was coordinated by the Consortium of College and University Media Centers during 1994-96, together with numerous participating organizations. The guidelines were recognized by the U.S. Congress in a Nonlegislative Report dated September 27, 1996.]

Indiana University. Copyright Management Center. <http://www.iupui.edu/~copyinfo/>
[Maintained as a resource for the academic community, this site offers access to resources about copyright and its importance to higher education. Topics of particular interest include fair use and distance learning.]

Library of Congress. *Copyright, Fair Use and Responsible Use of American Memory Collections.* <http://memory.loc.gov/ammem/ndlpedu/cpyright.html>
[The Library of Congress provides general information on copyright, fair use and questions related to classroom examples from teachers, using American Memory collections, digitized by the Library of Congress and available on the Library's website.]

Music Library Association. <http://www.musiclibraryassoc.org/>
[MLA's website on copyright, "A Guide to Copyright for Music Librarians".]

Software and Information Industry Association. <http://www.siia.net> <http://www.spa.org/piracy>
[SIIA, a trade association of the information industry, software developers and producers, conducts a comprehensive program of education, legal enforcement and public policy to fight the problem of software piracy; its education program provides tools for educators and others to help teach respect for copyright in software.]

Stanford University. <http://fairuse.stanford.edu/> <http://palimpsest.stanford.edu/bytopic/intprop>
[Websites on "Copyright and Fair Use" and "Copyright and Intellectual Property" with many documents and links related to libraries, education, copyright and fair use.]

University of Texas System. "Copyright Management Center Website." <http://www.utsystem.edu/OGC/intellectualproperty/cprtindx.htm>
[Contains many resources related to copyright in libraries and includes an interactive "Software and Database License Agreement Checklist."]

Washington State University. <http://www.publications.wsu.edu/copyright/copyright.html>
[Website for the University's Copyright Office with links to articles, fact sheets and guidelines on copyright.]

When Works Pass Into the Public Domain. <http://www.unc.edu/~unclng/public-d.htm>
[This chart, compiled by Laura N. Gasaway, outlines the duration of copyright for works covered by U.S. copyright law.]

Yale University. <http://www.library.yale.edu:80~okerson/copyright.html>
[Website with "Copyright Resources Online".]

Websites (for copyright licensing and permissions)

The following are some of the organizations which manage rights on behalf of rightsholders and provide copyright licensing and permissions services. Others provide helpful information for determining public domain works or for locating rightsholders.

Art Museum Image Consortium (AMICO) <http://www.amico.org/home.html>
[AMICO is a not-for-profit association of institutions with collections of art that have come together to enable educational use of the digital documentation in their collections through licensing educational access to museum multimedia documentation.]

Authors Registry. <http://www.webcom.com/registry>
[The Authors Registry is a non-exclusive licensor of author or agent-controlled rights including electronic and photocopy reproduction rights.]

Campus Custom Publishing, Inc. (CCP) <http://www.campuscp.com>
[CCP serves educational institutions and faculties' needs for compiling course-specific anthologies and other course materials, securing copyright permissions where necessary.]

Christian Copyright Licensing International (CCLI). <http://www.ccli.com>
[CCLI serves more than 140,000 churches worldwide to educate churches about copyright laws and provide licensing services for reproduction of church-related materials.]

Copyright Clearance Center (CCC). <http://www.copyright.com/resources/default.html>
[The CCC is a not-for-profit organization created in 1978 at the suggestion of the U.S. Congress to help organizations and individuals comply with U.S. copyright law through its licensing programs which provide authorized users with a lawful means for making photocopies from its repertory of over 1,750,000 titles.]

Graphic Artists Guild (GAG). <http://www.gag.org/pages/discipl.html>
[The GAG provides online portfolios of GAG members for permissions and licensing purposes]

Media Photographers Copyright Agency (MPCA). <http://www.mpca.com>
[MPCA is the licensing entity created by the American Society of Media Photographers to license its members' works in digital form, through a strategic alliance with the Copyright Clearance Center and Applied Graphics Technologies. MPCA licenses media photographs in digital form provided in the MIRA database.]

Motion Picture Licensing Corporation (MPLC). <http://www.mplc.com/index2.htm>
(MPLC is a copyright licensing service authorized by major Hollywood motion picture studios and independent producers to grant "umbrella" licenses to non-profit groups businesses and government organizations for public performances of home videocassettes and videodiscs.]

Music performing rights licensing organizations.
ASCAP <http://www.ascap.com/licensing/licensing.html>
BMI <http://www.bmi.com/licensing/index.html>
SESAC <http://www.sesac.com/license.htm>
[These music performing rights licensing organizations represent song writers and publishers and provide information about music licensing and copyrights.]

National Association of College Stores (NACS). <http://www.nacs.org/info/>
[The NACS website includes copyright information, Q&A concerning copyright compliance, procedures for obtaining permission to copy, including coursepack permission request forms and the guidelines for classroom copying.]

National Writers Union/Publications Rights Clearinghouse (NWU/PRC). <http://www.nwu.org>
[The Publications Rights Clearinghouse is the NWU agency that collects online royalties for freelance writers.]

National Music Publishers Association/Harry Fox Agency (HFA). <http://www.nmpa.org/hfa.html>
[The HFA, which represents over 20,000 American music publishers, was established by the National Music Publishers Association to license musical compositions for use on records, tapes, audio-visual works, CDs and

computer chips for private and commercial purposes.]

Picture Agency Council of America (PACA). <http://www.pacaoffice.org>

[PACA is the trade association for stock photography agencies in North America with almost 100 member agencies' names, addresses and contact information listed on the website. Image users can request a complimentary copy of the PACA membership directory by fax to the PACA Office--fax# 507-645-7066 or by email <info@pacaoffice.org>.]

WATCH: Writers, Artists and Their Copyright Holders.

<http://www.lib.utexas.edu/Libs/HRC/WATCH.html>

[The WATCH website is maintained by the Harry Ransom Humanities Research Center at the University of Texas at Austin and the University of Reading to help users locate copyright holders and to provide basic information about U.S. copyright law to researchers.]

ListServs

CNI-COPYRIGHT ListServ. <http://www.cni.org/Hforums/cni-copyright>

[An Internet discussion list on copyright and intellectual property related issues, with discussion among diverse contributors whc

LibLicense ListServ. Website and Listserv. <http://www.library.yale.edu/~Llicense/index.shtml>

[Licensing Electronic Resources, an Internet discussion list on library licensing issues and electronic content licensing for academic and research libraries, sponsored by Yale Univ. Lib., Commission on Preservation & Access, and Council on Library and Information Resources; includes sample license language and commentary.]

U.S. Copyright Office NEWSNET List Serv. <http://lcweb.loc.gov/copyright/newsnet>

[An electronic mailing list from the U.S. Copyright Office that sends periodic email messages, which alert subscribers to congressional and other hearings, new regulations, publications and other copyright-related subjects.]

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